TP 14139E

LOW TEMPERATURE IMPACT EFFECT ON TANK CARS

prepared for

Transportation Development Centre
and
Transport Dangerous Goods Directorate
of
Transport Canada
and
Federal Railroad Administration

by

Southwest Research Institute®
San Antonio, Texas, USA

and

National Research Council Canada
Centre for Surface Transportation Technology
Ottawa, Ontario, Canada

July 2003

103-06912/

TP 14139E

LOW TEMPERATURE IMPACT EFFECT ON TANK CARS

prepared by

Joseph W. Cardinal
Peter C. McKeighan

Southwest Research Institute®
San Antonio, Texas, USA

W. Nelson Caldwell
John R. Billing

National Research Council Canada
Centre for Surface Transportation Technology
Ottawa, Ontario, Canada

July 2003

NRC·CNRC

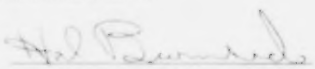
NOTICES

This report reflects the views of the authors and not necessarily those of the Transportation Development Centre of Transport Canada or the co-sponsoring agencies.

The Transportation Development Centre and the co-sponsoring agencies do not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

Since the accepted units in the industry are English, metric units are not used in this report.

APPROVED:



Hal Burnside, Ph.D., P.E., Director
Structural Engineering Department
Southwest Research Institute

Un sommaire français se trouve avant la table des matières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Recipient's Catalogue No.
TP 14139E	9636	

4. Title and Subtitle

Low Temperature Impact Effect on Tank Cars

5. Publication Date

July 2003

6. Performing Organization Document No.

SwRI 18.03298
CSTT RV122

7. Author(s)

J.W. Cardinal, P.C. McKeighan, W.N. Caldwell and J.R. Billing

8. Transport Canada File No.

2450-D-12-6

9. Performing Organization Name and Address

Southwest Research Institute
6620 Culebra Road
San Antonio, Texas
USA 78228-0510

National Research Council Canada
Centre for Surface Transportation Technology
U-89 Lester Road
Ottawa, Ontario
Canada K1A 0R6

10. PWGSC File No.

XSD-9-00382

11. PWGSC or Transport Canada Contract No.

T8200-9-5520/001/XSD

12. Sponsoring Agency Name and Address

Transportation Development Centre (TDC)
800 René Lévesque Blvd. West
Suite 600
Montreal, Quebec
H3B 1X9

13. Type of Publication and Period Covered

Final

14. Project Officer

B. Marshall

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by the Transport Dangerous Goods Directorate of Transport Canada and by the U.S. Federal Railroad Administration

16. Abstract

This report documents the literature and technology reviews performed by Southwest Research Institute® from October 1999 through December 2002, in parallel with related efforts at National Research Council Canada's Centre for Surface Transportation Technology (NRC/CSTT), to investigate the behavior and integrity of railroad tank cars subject to impact loads at low temperatures.

Work included a summary of the status of the North American tank car fleet and its operating environment; a review of yard impact accidents occurring in the United States and Canada; a detailed description of draft gear specifications, draft gear behavior under impact loading, mathematical models describing the coupling event, and results of full-scale impact tests; a discussion of tank car steel material properties, their performance under low temperature and dynamic load conditions, and standard measurement and testing techniques; and a summary of tank car design and analysis practices, with an emphasis on what types of analyses are appropriate for the low temperature impact problem.

Recommendations as a result of these efforts are provided regarding operational techniques, tank car impacts and draft gear behaviour, fracture safe design, fracture toughness and probabilistic risk analysis.

17. Key Words	18. Distribution Statement
Railroad tank car, low temperature performance, coupling impact, fracture mechanics, structural analysis, draft gear performance, toughness	Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	—	xiv, 70, apps	Shipping/ Handling

Transports Canada / Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada	2. N° de l'étude	3. N° de catalogue du destinataire
TP 14139E	9636	

4. Titre et sous-titre	5. Date de la publication
Low Temperature Impact Effect on Tank Cars	Juillet 2003
	6. N° de document de l'organisme exécutant SwRI 18.03298 CSTT RV122

7. Auteur(s)	8. N° de dossier - Transports Canada
J.W. Cardinal, P.C. McKeighan, W.N. Caldwell et J.R. Billing	2450-D-12-6

9. Nom et adresse de l'organisme exécutant		10. N° de dossier - TPSGC
Southwest Research Institute 6620 Culebra Road San Antonio, Texas USA 78228-0510	Conseil national de recherches du Canada Centre de technologie des transports de surface U-89 Lester Road Ottawa, Ontario Canada K1A 0R6	XSD-9-00382
		11. N° de contrat - TPSGC ou Transports Canada T8200-9-5520/001/XSD

12. Nom et adresse de l'organisme parrain	13. Genre de publication et période visée
Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9	Final
	14. Agent de projet B. Marshall

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Projet coparrainé par la Direction générale du transport de marchandises dangereuses de Transports Canada et la Federal Railroad Administration des États-Unis

16. Resumé

Le présent rapport rend compte de la recherche documentaire et de la revue de la technologie effectuées par le Southwest Research Institute® entre octobre 1999 et décembre 2002, parallèlement aux études réalisées au Centre de technologie des transports de surface du Conseil national de recherches du Canada (CTTS/CNRC) sur le comportement et l'intégrité des wagons-citernes soumis à des forces d'impact à basse température.

Les travaux ont comporté un inventaire sommaire de la situation du parc nord-américain de wagons-citernes et des conditions d'exploitation de ces wagons; une revue des accidents par impact survenus dans les cours de triage du Canada et des États-Unis; un examen détaillé des spécifications relatives aux appareils de traction, du comportement de l'appareil de traction soumis à une force d'impact, des modèles mathématiques représentant les manœuvres d'accouplement de wagons, et des résultats d'essais aux chocs en vraie grandeur; une discussion des propriétés de l'acier dont sont faits les wagons-citernes, de la performance de ce matériau à basse température et dans des conditions de charge dynamique, et des techniques standard de mesure et d'essai; et une synthèse des méthodes de conception et d'analyse touchant les wagons-citernes, avec une attention particulière portée aux types d'analyses appropriés à l'étude du problème des chocs à basse température.

Ces travaux ont donné lieu à des recommandations concernant les techniques d'exploitation, les chocs subis par les wagons-citernes et le comportement de l'appareil de traction, la conception anti-rupture, la résistance à la rupture et l'analyse probabiliste du risque.

17. Mots clés	18. Diffusion
Wagon-citerne, performance à basse température, impact d'accostage, mécanique de la rupture, analyse structurale, performance des appareils de traction, ténacité	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xiv, 70, ann.	Port et manutention

CDT/TDC 79-005
Rev. 96

Canada

EXECUTIVE SUMMARY

From October 1999 through April 2003, Southwest Research Institute® (SwRI®) and National Research Council Canada's Centre for Surface Transportation Technology (NRC/CSTT) investigated the behavior and integrity of railroad tank cars subject to impact loads at low temperatures. SwRI was the prime contractor for the overall project. The project technical monitor was Mr. Douglas W. Dibble of Transport Canada.

SwRI's effort on this project focused on areas dealing with material behavior, fracture mechanics and the application of structural analysis results to the development of failure criteria. The NRC/CSTT effort addressed draft gear performance, the absorption of impact forces into the tank car structure, and operational factors involved in controlling coupling impacts. While both organizations investigated accident reports in the United States and Canada, the overall focus of the project was confined to yard impacts (collisions) that are a result of the coupling process. Accidents such as derailments were generally excluded from the study.

Key Findings

- Tank car accident information (databases) provide a wealth of historical data that can be used to categorize accident scenarios by developing statistical distributions of event conditions. These actual data can be compared to operational goals and/or observed day-to-day norms (non-accident data).

- The most common overspeed yard coupling events are significantly more severe than the 5 mph event specified for rating draft gear. Furthermore, the types of draft gear most widely used in tank cars may reach their rated capacity well below 5 mph. Flat yards or hump yards that aim to couple at an average speed of 4 mph are likely to have a significant number of couplings occur at speeds in excess of 5 mph. Coupling at a speed above the impact velocity rating of the draft gear may drive the gear solid, causing the peak force to increase to a rate four to five times that which occurs when the draft gear provides impact cushioning.

- No data were found in the literature relating to the low temperature performance of draft gear. Very limited data were available from draft gear manufacturers. NRC/CSTT conducted limited full-scale impact tests to measure the performance of a steel friction wedge draft gear under low temperature and ambient temperature conditions. These tests indicated that there was a significant loss of rated energy capacity for the cold draft gear case.

- The capacity of a friction draft gear is significantly reduced when its friction surfaces are contaminated by frost and is also somewhat reduced by wear. The resistance of an elastomeric friction draft gear increases significantly at low temperature. There are no performance requirements for draft gear at low temperature.

- The most critical situation for a tank car probably arises when it is at the head of a long string of anvil cars, and a cut of two or more loaded hammer cars couples to it. The simple case of coupling one hammer car, with an initial velocity, to one stationary anvil car, as specified in AAR M901G, is not typical of most of the couplings conducted in flat yard or hump yard switching, nor does it represent an extreme load condition.

- Tank cars built prior to 1974 with a nominal buff capacity of 800,000 lb. have a much higher risk of yield as a consequence of a severe coupling impact than cars built subsequent to that date having a buff capacity of 1,250,000 lb.

- Two decades ago there was an initiative made to implement a fracture mechanics based technology to address the combination of low temperature and dynamic loadings in railroad tank cars. However, these methods are not in common use today. Since the sole method of addressing these issues today is by specifying a Charpy energy requirement for tank car steels, the tank car industry has not kept pace with the advances in structural integrity technology that have been made in other industries that rely on welded steel structures. It is recommended that the "fracture-safe design" technology and guidelines put forward 20 years ago by Pellini be modernized to take advantage of advances in technology made over the last two decades.

- Much attention has been given over the years to improving the toughness characteristics of steels used in tank car construction; there are numerous references in the tank car literature documenting how new materials with increased toughness will affect accidents. The problem with this earlier work is that datasets available for the materials are few. Perhaps most importantly, the service environment typical of tank car operation has not been applied in the materials test laboratory when generating these data.

- The occurrence of failures under low temperature impact conditions is most likely a statistical variability issue that is exacerbated and not fully understood due to limited testing budgets and few replicate specimens. If operating conditions were farther away from the lower shelf temperature, this would be less of an issue, but in the region where toughness is changing as a function of temperature, a significant amount of variability in properties can be observed. Combining this variability with scatter due to lot-to-lot material variations, the presence of welds, and uncertain loading rates may result in higher risk due to larger overall "system" variability that is not particularly well understood or quantified.

SOMMAIRE

D'octobre 1999 à avril 2003, le Southwest Research Institute® (SwRI®) et le Centre de technologie des transports de surface du Conseil national de recherches du Canada (CTTS/CNRC) ont mené une étude sur le comportement et l'intégrité de wagons-citernes soumis à des forces d'impact à basse température. Le SwRI était le contractant principal pour l'ensemble du projet et le responsable technique du projet était M. Douglas W. Dibble de Transports Canada.

Les travaux du SwRI ont surtout porté sur le comportement des matériaux, la mécanique de la rupture et l'application des résultats d'analyse structurale à l'élaboration de critères de défaillance. Pour sa part, le CTTS du CNRC s'est penché sur les performances de l'appareil de traction, l'absorption des forces d'impact dans la structure du wagon-citerne, et les facteurs reliés à l'exploitation qui permettent d'atténuer les chocs à l'accostage. Les deux organismes ont dépouillé des rapports d'accidents survenus aux États-Unis et au Canada, mais l'objet de leur recherche se limitait aux chocs (collisions) résultant des opérations de composition des trains dans les gares de triage. Les accidents assimilables à des déraillements étaient généralement exclus de l'étude.

Principaux résultats

- Les bases de données sur les accidents de wagons-citernes contiennent une grande quantité de données historiques qui peuvent servir à classer les scénarios d'accidents par catégories, en établissant des distributions statistiques des conditions d'accidents. Ces données réelles peuvent être mises en rapport avec les objectifs opérationnels et/ou les normes appliquées au jour le jour (données hors accident).

- Les survitesses d'accostage les plus courantes dans les gares de triage dépassent largement les 5 mi/h de vitesse maximale spécifiée pour l'appareil de traction. Sans compter que les types d'appareils de traction les plus couramment utilisés sur les wagons-citernes atteignent parfois leur capacité nominale bien en deçà de 5 mi/h. Dans les triages en palier ou les triages à butte conçus pour que les manœuvres d'accouplement se fassent à une vitesse moyenne de 4 mi/h, il est probable que les vitesses d'accostage dépassent souvent 5 mi/h. Or, un accostage à une vitesse supérieure à la vitesse spécifiée pour l'appareil de traction peut surcharger l'appareil au point de le rendre inopérant, et engendrer ainsi une force de pointe qui atteint quatre fois, voire cinq fois, la force de pointe mesurée lorsque l'appareil de traction joue son rôle d'amortisseur.

- La recherche documentaire n'a pas permis de recueillir de données sur les performances des appareils de traction à basse température. Et les fabricants de ces appareils ont fourni des données très limitées sur le sujet. Le CTTS du CNRC a pour sa part mené quelques essais aux chocs en vraie grandeur pour mesurer les performances d'un appareil de traction à friction à basse température et à température dite ambiante (normale). Ces essais ont révélé une importante perte de la capacité d'amortissement nominale de l'appareil de traction à basse température.

- La capacité d'amortissement d'un appareil de traction à friction se trouve considérablement réduite lorsque les surfaces des parties frottantes sont contaminées par du givre, et elle est aussi quelque peu réduite par l'usure de ces surfaces. Aussi, la dureté d'un appareil de

traction à friction en élastomère augmente beaucoup à basse température. Il n'existe pas de normes de performance applicables aux appareils de traction à basse température.

- La situation la plus critique pour un wagon-citerne est probablement celle qui se produit lorsqu'il est le premier d'une longue rame de wagons-enclumes, et que deux wagons-béliers chargés ou plus s'y attellent. L'attelage d'un seul wagon-bélier, animé d'une vitesse initiale, à un seul wagon-enclume stationnaire, comme il est précisé dans la norme M901G de l'AAR, n'est pas typique de la plupart des manœuvres d'attelage exécutées dans les triages en palier ou dans les triages à butte, pas plus qu'il ne présente une condition de charge extrême.

- Les wagons-citernes fabriqués avant 1974, dotés d'une résistance aux chocs nominale de 800 000 lb, risquent beaucoup plus de se rompre par suite d'un accostage violent que les wagons construits par la suite, dont la résistance aux chocs atteint 1 250 000 lb.

- Il y a une vingtaine d'années, des chercheurs se sont tournés vers une technologie fondée sur la mécanique de la rupture pour aborder le problème de la basse température combinée au chargement dynamique dans les wagons-citernes. Mais aujourd'hui, ces méthodes sont presque tombées dans l'oubli. Étant donné que, encore à l'heure actuelle, la seule façon d'établir les propriétés des aciers pour wagons-citernes est de spécifier un essai de résilience Charpy, l'industrie des wagons-citernes n'a pas suivi les progrès accomplis par la technologie de l'intégrité structurale, comme l'ont fait les autres industries qui utilisent des structures en acier soudé. Il est recommandé de moderniser la technologie et les lignes directrices de «conception anti-rupture» préconisées par Pellini il y a 20 ans et d'y incorporer les progrès technologiques réalisés ces deux dernières décennies.

- L'amélioration de la ténacité des aciers utilisés dans la construction des wagons-citernes a suscité beaucoup d'intérêt ces dernières années. En effet, la recherche documentaire a mené à plusieurs articles spécialisés qui font un lien entre les nouveaux matériaux, plus tenaces, et les accidents. Mais un problème se pose : il existe peu d'ensembles de données sur les matériaux étudiés. Et, encore plus important peut-être, ces données résultent d'essais menés dans des laboratoires où n'était pas pris en compte l'environnement dans lequel les wagons-citernes sont exploités.

- Les défaillances dues à des forces d'impact à basse température sont très probablement sujettes à la variabilité statistique, laquelle est encore mal comprise du fait des maigres budgets alloués aux essais et de la rareté des échantillons répétés pour ces essais. Aux températures d'exploitation éloignées des températures de fragilisation, le problème se pose moins, mais dans la région où la ténacité fluctue en fonction de la température, les propriétés des matériaux se révèlent très variables. Cette variabilité, combinée à la dispersion des données due aux différences entre matériaux d'un lot à l'autre, à la présence de soudures, et à des taux de chargement incertains, peut engendrer un risque accru de défaillance, attribuable à la variabilité accrue du «système» global, qui est encore loin d'être bien comprise.

TABLE OF CONTENTS

Page

1.0 INTRODUCTION 1

2.0 THE TANK CAR FLEET AND ITS OPERATING ENVIRONMENT 2

2.1 The Tank Car Fleet 2
2.2 The Operating Environment 7

3.0 REVIEW OF ACCIDENTS AND FAILURES 10

3.1 United States 10
3.1.1 Industry Input 10
3.1.2 Accident Databases 10
3.1.3 Documented "Brittle" Fractures 13
3.2 Canada 15
3.3 Bibliography of Accident Reports 16

4.0 THE ROLE OF DRAFT GEAR IN TANK CAR COUPLING IMPACT 17

4.1 Introduction 17
4.2 Draft Gear Specifications 17
4.2.1 AAR Specification M901E 17
4.2.2 Draft Gear Energy Absorption 18
4.2.3 Certification Temperature Requirements and Low Temperature Laboratory Tests 21
4.2.4 Draft Gear Reconditioning Requirements 23
4.2.5 AAR Specification M901G 24
4.3 Mathematical Relationships for Coupling Impact 25
4.3.1 Experimental Confirmation of the Theory 26
4.3.2 The Consequences of Coupling at Speeds above the Impact Velocity Rating 28
4.3.3 The Protection Effect of Fluid Loads with Tank Outage 29
4.3.4 Revenue Coupling Scenarios 32
4.3.5 Mathematical Relationships for Multi-car Couplings 33
4.3.6 Full-scale Multi-car Impact Tests 36
4.3.7 Using the Calibrated KE Method to Extrapolate to 263,000 lb. Cars 39
4.3.8 Distribution of Coupling Impact Speeds 40
4.4 Full-scale Draft Gear Tests at Low and Warm Temperatures 40

5.0 TANK CAR STEEL MATERIAL PROPERTIES 47

5.1 Property Definitions 47
5.1.1 Toughness Measures Using Methods prior to the Development of Fracture Mechanics 47

5.1.2 Toughness Measures Derived from Fracture Mechanics Methods 49
5.2 Test Methods and Standards 52
5.3 Literature Summary 54

6.0 DESIGN AND ANALYSIS PRACTICES 57

6.1 Current Approaches 57
6.2 Fracture Analysis Procedures 58
6.3 Impact Loading 58

7.0 CONCLUSIONS AND RECOMMENDATIONS 60

7.1 Operational 60
7.2 Tank Car Impacts and Draft Gear Behavior 60
7.3 Fracture Safe Design 61
7.4 Fracture Toughness 62
7.5 Probabilistic Risk Analyses 64

REFERENCES 65

APPENDIX A - SUBSET OF RPI-AAR TANK CAR ACCIDENT DATABASE CONTAINNG YARD IMPACTS AT LESS THAN 50°F

APPENDIX B - SUMMARY OF CANADIAN TANK CAR ACCIDENTS

APPENDIX C - BIBLIOGRAPHY

APPENDIX D - BRIEF SUMMARY OF PELLINI'S FRACTURE ANALYSIS METHODOLOGY

LIST OF FIGURES

Figure		Page
1.	Cumulative Age Distribution of Tank Cars	4
2.	Number of Yard Impact Accidents as a Function of Speed at Temperatures Less than 50°F [6]	11
3.	Number of Yard Impact Events as a Function of Temperature [6]	11
4.	Yard Impact Speed vs. Temperature [6]	12
5.	Venn Diagram of Tank Car Accidents in which Tank Car Failure Released Product	16
6.	Cutaway View of the Miner SL-76 Friction/Rubber Draft Gear, M901E Rating Specification, and Reaction Force-Travel Curve	19
7.	Cutaway View of a Cardwell-Westinghouse Mark 50 All Steel Friction Draft Gear, M901E Rating Specification, and Reaction Force-Travel Curve	20
8.	Draft Gear Buff Peak Reaction Force at Rated Travel Input at Four Test Temperatures (ambient, 0°F, –20°F, and –40°F)	22
9.	Miner Model SL-76 Measured Draft Gear Capacity after Eight Years and One Million Miles in Revenue Unit Train Coal Service	23
10.	Impact Velocity Rating Test Results (Average) for New Steel M901E Draft Gears Tested as per M901G for Impact Velocity Rating	28
11.	Tank Sector Semi-Angle vs. Tank Outage for Cylindrical Tanks	31
12.	Non-Dimensional Ratio for Fluid CG, Segment CG, and Tank Outage for Cylindrical Tanks and Undisturbed Fluid as a Function of Tank Outage	31
13.	Final Velocity Factor after Multi-car Coupling Impact for 1, 2, and 3 Hammer Cars Coupling into from 1 to 50 Anvil Cars	34
14.	Kinetic Energy Loss Ratio for Multi-car Coupling Impact for 1, 2, and 3 Hammer Cars Coupling into from 1 to 50 Anvil Cars	35
15.	Comparison of Measured Multi-tank Car Impact Velocities, which Produced a 500,000 lb. Peak Draft Gear Force, with Kinetic Energy Impact Model Calibrated to Match the Measured Data, with All Tank Cars Loaded to 169,000 lb. GRL	38
16.	Foam Board Thermal Housing Applied to Coupler/Sill Area of Both Cars during Cooling of Draft Gears with Expanded Liquid Nitrogen Gas	44
17.	Interior of Cold Housing after Cool Down of Couplers, Draft Gears, and Sill Area, Cold Housing is Being Disassembled to Start Testing	44
18.	Underside of Sill Showing the LVDT and String Pot Transducers to Capture Draft Gear Buff Stroke	45
19.	Hammer and Anvil Cars Coupled with Frosting Seen on Couplers and Sills	45
20.	Draft Gear Peak Impact Force vs. Coupling Speed for Cold and Warm Conditions	46

LIST OF TABLES

Table		Page
1.	North American Tank Car Fleet by Type and Year of Manufacture	3
2.	Type of Shell Steel of Non-pressure Tank Cars by Year of Manufacture	5
3.	Type of Shell Steel of Pressure Tank Cars by Year of Manufacture	6
4.	Location and Temperatures of Major Hump Yards in North America	8
5.	Yard Impact Accidents (from 1981 to 1994) Characterized as Brittle Fractures in Ref. [8]	14
6.	Car Kinetic Energy for Various Speeds and Gross Weights on Rail	26
7.	Coupling Speeds for Various Draft Gear Energy Ratings and Selected Car Gross Rail Loads	27
8.	Comparison of Theoretical and Measured Impact Velocity Ratings for New Steel M901E Draft Gears Tested per M901G	28
9.	Comparison of Measured Multi-tank Car Impact Velocities, which Produced a 500,000 lb. Peak Draft Gear Force, with Kinetic Energy Impact Model Calibrated to Match the Measured Data, all Tank Cars Loaded to 169,000 lb. GRL	38
10.	Combinations of Multi-tank Car Coupling Speeds for 500,000 lb. Peak Coupler Forces for Different Draft Gear Rated Energy Capacities	39
11.	Number of Couplings per Million Couplings that Exceed a Given Impact Speed, for Various Standard Deviations in Coupling Impact Speed with a Mean of 4 mph	41
12.	Number of Days for One Million Couplings, Based on Hump Yard Productivity and Average Number of Cars in a Hammer String	41
13.	Description of the Relevant ASTM Standard Associated with Each Test Method	53
14.	Summary of Tank Car Steel Material Property Data References	56

LIST OF ABBREVIATIONS

ORGANIZATIONS:

AAR	Association of American Railroads
ASTM	American Society for Testing and Materials
CSTT	Centre for Surface Transportation Technology
CTC	Canadian Transportation Commission
DOT	U.S. Department of Transportation
FRA	U.S. Federal Railroad Administration
NRC	National Research Council Canada
NTSB	U.S. National Transportation Safety Board
PWGSC	Public Works and Government Services Canada
RPI	Railroad Progress Institute
SSWG	Stub Sill Working Group
SwRI	Southwest Research Institute
TC	Transport Canada
TCOE-TF	Tank Car Operating Environment Task Force
TDC	Transportation Development Centre
TSB	Transportation Safety Board of Canada
TTCI	Transportation Technology Center, Inc.

TECHNICAL TERMS:

CG	Center of Gravity
CTOD	Crack Tip Opening Displacement
CVN	Charpy V-Notch
DT	Dynamic Tear
DWT	Drop Weight Tear
EPFM	Elastic Plastic Fracture Mechanics
FAD	Failure Assessment Diagram
LCF	Longitudinal Coupler Force
LEFM	Linear Elastic Fracture Mechanics
NDT	Nil-ductility Transition (temperature)
OTR	Over-the-road
RAIRS	Railroad Accident Incident Reporting System
UMLER	Universal Machine Language Equipment Register
VCF	Vertical Coupler Force

1.0 INTRODUCTION

This report documents the literature and technology reviews that Southwest Research Institute® (SwRI®) has performed, in parallel with related efforts at National Research Council Canada's Centre for Surface Transportation Technology (NRC/CSTT), to investigate the behavior and integrity of railroad tank cars subject to impact loads at low temperatures. The report documents work performed during the period from October 1999 through April 2003.

SwRI's effort on this project focused on areas dealing with material behavior, fracture mechanics and the application of structural analysis results to the development of failure criteria. The NRC/CSTT effort addressed draft gear performance, the absorption of impact forces into the tank car structure, and operational factors involved in controlling coupling impacts. While both organizations investigated accident reports in the United States and Canada, the overall focus of the project was yard impacts (collisions) that are a result of the coupling process. Accidents such as derailments were generally excluded from the study unless a report provided relevant material property information.

This report contains six principal sections summarizing a number of different investigations performed by SwRI and NRC/CSTT. A summary of the status of the North American tank car fleet and its operating environment is first presented in Section 2.0, while Section 3.0 presents a review of yard impact accidents occurring in the United States and Canada. Section 4.0, the largest chapter of the report, provides a detailed description of draft gear specifications, draft gear behavior under impact loading, mathematical models describing the coupling event, and the results of full-scale impact tests conducted at NRC/CSTT. Tank car steel material properties, their performance under low temperature and dynamic load conditions, as well as standard measurement and testing techniques, are discussed in Section 5.0. A summary of tank car design and analysis practices is provided in Section 6.0, with an emphasis on what types of analyses are appropriate for the low temperature impact problem. Conclusions and recommendations as a result of these efforts are then provided in Section 7.0.

A subset of the RPI-AAR Tank Car Accident Database that was a key resource for this effort is contained in Appendix A. Appendix B contains a summary of Canadian tank car accidents. Appendix C provides a bibliography of many of the reports reviewed by SwRI on this project. Individual sections of the report refer to specific references as appropriate; however, many of the references listed in Appendix C are not directly referenced by the text. Appendix C is provided to document this material for future reference as needed. Finally, a brief summary of the fracture analysis methodology put forward by Pellini in the late 1970s and early 1980s is provided in Appendix D for reference.

2.0 THE TANK CAR FLEET AND ITS OPERATING ENVIRONMENT

2.1 The Tank Car Fleet

The tank car fleet consists of non-pressure designs in classes DOT-103 and DOT-111, pressure designs in classes DOT-105 and DOT-112, and small numbers of specialized designs [1]. Table 1 summarizes the tank c fleet by car t e, i.e. non-pressure or pressure, construction material, and year of construction for tank cars built up to the end of 2002, and registered as of 16 March 2003 [2]. It includes about 20,000 tank cars based in Canada tha meet DOT and AAR interchange requirements. It excludes non-pressure and specialized tank cars built to AAR specifications for carriage of commodities not regulated by DOT, tank cars designated as scrap, tank cars prohibited fr interchange service by AAR or FRA rules, and any articulated tank cars. An articulated tai ar is a car with two or more permanently coupled units that share a bogie.

Class DOT-103 defines a non-pressure tank car with a center sill and an expansion dome whose original design dates back to the ICC specifications of 1927. It was replaced by the DOT-111 domeless non-pressure stub sill design in the 1960s. These two classes make up most of the 78 percent of the North American tank car fleet that are non-pressure cars.

Class DOT-105 defines an insulated pressure ta car whose original design also dates back to the ICC specifications of 1927. DOT-112 is a pressure tank car introduced in the 1950s, with a larger tank than DOT-105. The class was originally not insulated, but now it includes thermally protected cars. These two classes make up most of the 22 percent of the North American tank car fleet that are pressure cars.

The North American tank car fleet is currently composed of about 270,000 tank cars, which is about 18 percent of all freight cars. Tank cars are almost exclusively (99.7 percent) owned by leasing companies or shippers, not by railroads. Tank cars are moved by railroads, but at the direction of shippers. About 99.3 percent of all tank cars are made of steel, which includes small numbers made of stainless steel. The remainder are made of aluminum. About 212,000, or 78 percent, are non-pressure tank cars, and the remaining 59,000, or 22 percent, are pressure tank cars. Figure 1 shows a cumulative age distribution for tank cars. The curves indicate the percentage of cars built prior to any date. The data shown are for non-pressure tank cars, pressure tank cars, and all tank cars. The difference between pressure and non-pressure cars is that a greater proportion of pressure tank cars were built between about 1965 and 1980 than their current proportion in the overall population.

Only 26 tank cars, all but one built between 1967 and 1977, are equipped with hydraulic draft gear. All other tank cars are equipped with standard draft gear in a 24-5/8 in. pocket. Only 99 tank cars built from 1965 to 1982, and one built in 2002, have no shelf on the coupler. Only 15 tank cars, built from 1973 to 1995, have just a bottom shelf. All others have a coupler with a double shelf [2].

Table 1. North American Tank Car Fleet by Type and Year of Manufacture

Year	Steel Non-press.	Steel Pressure	Other Non-press.	Other Pressure	Total	Percent of Total	Cum. Percent
1956	0	2	0	0	2	0.00	0.00
1957	1	2	0	3	6	0.00	0.00
1958	0	2	0	1	3	0.00	0.00
1959	0	0	0	0	0	0.00	0.00
1960	3	0	0	0	3	0.00	0.01
1961	1	0	0	0	1	0.00	0.01
1962	0	1	0	0	1	0.00	0.01
1963	261	519	23	0	803	0.30	0.30
1964	527	871	51	0	1449	0.54	0.84
1965	895	954	108	0	1957	0.72	1.56
1966	1502	1834	69	7	3412	1.26	2.82
1967	1928	1951	124	0	4003	1.48	4.30
1968	2540	1865	83	4	4492	1.66	5.96
1969	3750	2459	66	5	6280	2.32	8.28
1970	3598	2291	73	0	5962	2.20	10.49
1971	3006	1247	42	0	4295	1.59	12.08
1972	3294	560	27	0	3881	1.44	13.51
1973	6260	1099	23	0	7382	2.73	16.24
1974	8084	1191	58	0	9333	3.45	19.69
1975	6314	1317	57	0	7688	2.84	22.53
1976	3128	1405	111	0	4644	1.72	24.25
1977	5244	1986	16	0	7246	2.68	26.92
1978	6465	1968	20	0	8453	3.12	30.05
1979	7892	2046	45	0	9983	3.69	33.74
1980	10837	2893	36	0	13766	5.09	38.83
1981	8567	1966	89	0	10622	3.93	42.75
1982	3861	810	12	0	4683	1.73	44.48
1983	2587	106	14	0	2707	1.00	45.48
1984	3714	246	35	0	3995	1.48	46.96
1985	3018	318	50	0	3386	1.25	48.21
1986	2806	253	59	259	3377	1.25	49.46
1987	5332	463	10	0	5805	2.15	51.61
1988	5172	1184	46	0	6402	2.37	53.97
1989	7085	846	22	0	7953	2.94	56.91
1990	6037	1283	62	0	7382	2.73	59.64
1991	4306	1502	11	0	5819	2.15	61.79
1992	4387	1351	0	0	5738	2.12	63.91
1993	5895	936	12	0	6843	2.53	66.44
1994	7935	957	32	0	8924	3.30	69.74
1995	9880	2300	35	0	12215	4.51	74.25
1996	7501	3920	2	0	11423	4.22	78.48
1997	7716	2160	0	0	9876	3.65	82.13
1998	10229	2681	0	0	12910	4.77	86.90
1999	10653	1832	0	0	12485	4.61	91.51
2000	8214	2051	0	0	10265	3.79	95.31
2001	5525	1753	0	0	7278	2.69	98.00
2002	4124	1295	0	0	5419	2.00	100.00
Total	**210074**	**58676**	**1523**	**279**	**270552**		
Percent	**77.65**	**21.69**	**0.56**	**0.10**	**100.00**		

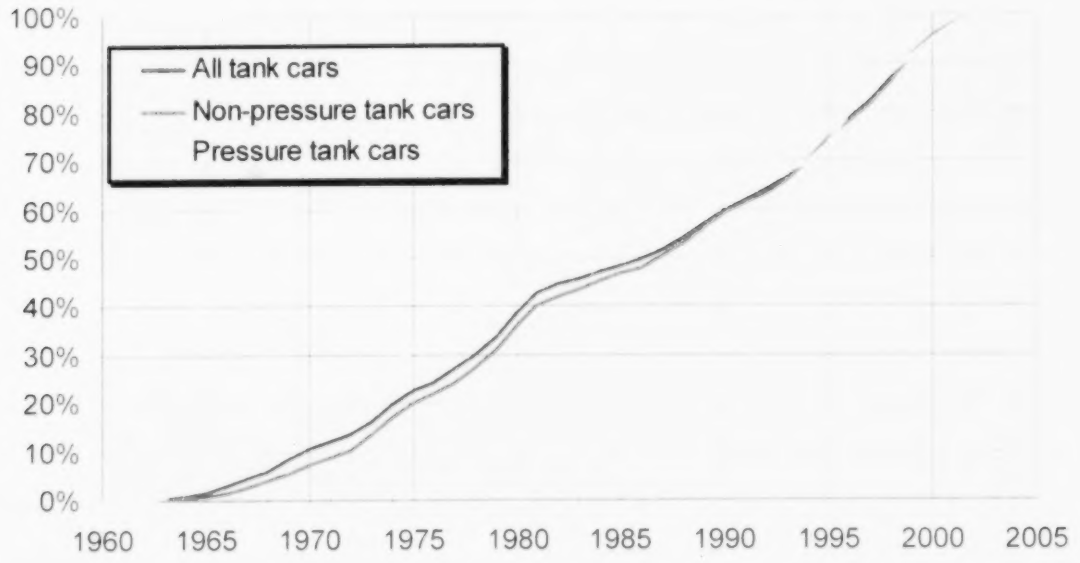


Figure 1. Cumulative Age Distribution of Tank Cars

Tables 2 and 3 show the grades of steel used in the shell of non-pressure and pressure cars respectively, by year of manufacture of the tank car per the UMLER database [2]. The columns are ordered by decreasing order of overall use of grade of steel. The "other" category includes AAR TC128 Grade A, ASTM A516 Grade 70-316L, ASTM A515 Grade 70-304L, ASTM A240 Type 304, ASTM A537 C1.1, ASTM A240 Type 316, ASTM A515 Grade 60 and ASTM A537 Grade A, listed in decreasing overall usage. Note that the UMLER file does not contain these data for 63,894, or 30.41 percent, of 210,074 non-pressure tank cars, and for 12,996, or 22.15 percent, of 58,676 pressure tank cars. Together these represent 28.6 percent of all tank cars. Complete data have only been available since 1997. There is no evident sound way to estimate the actual breakdown of grade of steel for the unknown cars from the known data. Table 2 shows how A516 and TC128 steels have replaced A515 steel for non-pressure cars since the change of regulations in 1989, and Table 3 shows how TC128 steel has continuously dominated for pressure cars. The UMLER data file also identifies the head material, and similar data could be derived. The head and shell use different steels for 19,640, or 10.2 percent, of 193,439 tank cars where both materials are identified.

Among the materials under the "other" category, only AAR TC128 Grade A, ASTM 516 Grade 70-316L and ASTM 515 Grade 70-304L have been used from 1989 on non-pressure cars, and only AAR TC128 Grade A and ASTM 240 Type 304 have been used on pressure cars. It is somewhat surprising that AAR TC128 Grade A was reported as the shell material on several lots of non-pressure cars built in 1995, 1996 and 1997, and one lot of pressure cars built in 2002. The head was also reported as the same material for all but one of these lots of cars. The tables simply summarize the data report received from the UMLER database [2].

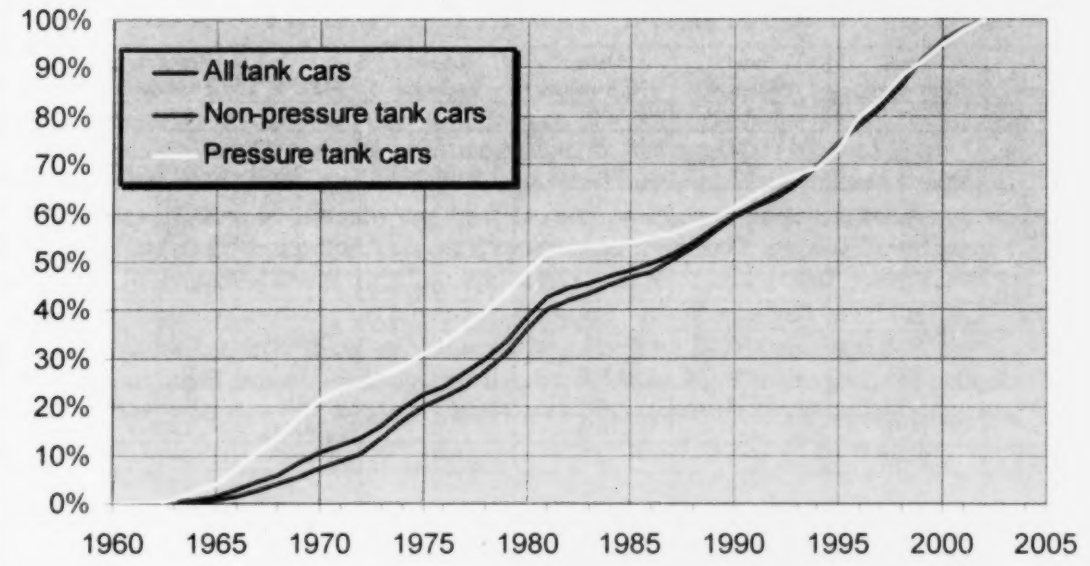


Figure 1. Cumulative Age Distribution of Tank Cars

Tables 2 and 3 show the grades of steel used in the shell of non-pressure and pressure cars respectively, by year of manufacture of the tank car per the UMLER database [2]. The columns are ordered by decreasing order of overall use of grade of steel. The "other" category includes AAR TC128 Grade A, ASTM A516 Grade 70-316L, ASTM A515 Grade 70-304L, ASTM A240 Type 304, ASTM A537 C1.1, ASTM A240 Type 316, ASTM A515 Grade 60 and ASTM A537 Grade A, listed in decreasing overall usage. Note that the UMLER file does not contain these data for 63,894, or 30.41 percent, of 210,074 non-pressure tank cars, and for 12,996, or 22.15 percent, of 58,676 pressure tank cars. Together these represent 28.6 percent of all tank cars. Complete data have only been available since 1997. There is no evident sound way to estimate the actual breakdown of grade of steel for the unknown cars from the known data. Table 2 shows how A516 and TC128 steels have replaced A515 steel for non-pressure cars since the change of regulations in 1989, and Table 3 shows how TC128 steel has continuously dominated for pressure cars. The UMLER data file also identifies the head material, and similar data could be derived. The head and shell use different steels for 19,640, or 10.2 percent, of 193,439 tank cars where both materials are identified.

Among the materials under the "other" category, only AAR TC128 Grade A, ASTM 516 Grade 70-316L and ASTM 515 Grade 70-304L have been used from 1989 on non-pressure cars, and only AAR TC128 Grade A and ASTM 240 Type 304 have been used on pressure cars. It is somewhat surprising that AAR TC128 Grade A was reported as the shell material on several lots of non-pressure cars built in 1995, 1996 and 1997, and one lot of pressure cars built in 2002. The head was also reported as the same material for all but one of these lots of cars. The tables simply summarize the data report received from the UMLER database [2].

Table 2. Type of Shell Steel of Non-pressure Tank Cars by Year of Manufacture

Year	Not known	ASTM A516 Gr 70	AAR TC128 GrB	ASTM A515 Gr 70	ASTM A285 Gr C	A516 Gr 70 & TC128	ASTM A212 Gr B	ASTM A240 T316L	ASTM A240 T304L	A515 Gr70 & TC128	Other
1956	0	0	0	0	0	0	0	0	0	0	0
1957	0	0	1	0	0	0	0	0	0	0	0
1958	0	0	0	0	0	0	0	0	0	0	0
1959	0	0	0	0	0	0	0	0	0	0	0
1960	0	0	0	0	0	0	3	0	0	0	0
1961	1	0	0	0	0	0	0	0	0	0	0
1962	0	0	0	0	0	0	0	0	0	0	0
1963	93	0	7	40	33	0	77	0	10	0	1
1964	258	0	28	70	62	0	107	0	1	0	1
1965	375	2	0	24	131	0	360	2	0	0	1
1966	543	1	2	279	330	0	340	0	3	1	3
1967	691	8	2	791	264	0	161	3	4	4	0
1968	971	42	38	1273	168	0	26	10	8	4	0
1969	1725	10	35	1758	211	0	4	5	0	2	0
1970	1275	29	1	2035	210	0	6	8	2	31	1
1971	1276	37	77	1344	256	0	0	0	12	0	4
1972	1420	121	1	1426	315	0	0	0	2	0	9
1973	2592	357	45	2828	350	0	2	0	66	20	0
1974	2731	509	163	3915	709	0	0	0	24	26	7
1975	1718	768	115	2992	615	0	0	0	53	22	31
1976	1295	43	13	1631	127	0	0	0	0	19	0
1977	1463	237	26	3239	271	0	0	0	1	5	2
1978	2387	127	69	3702	177	0	0	0	0	3	0
1979	3029	257	320	3838	339	0	0	0	40	69	0
1980	4689	314	12	5407	255	0	0	0	31	100	29
1981	3748	477	21	4005	126	0	0	5	20	161	4
1982	1622	655	278	1281	2	10	0	0	0	13	0
1983	1286	1	135	1145	0	0	0	0	20	0	0
1984	1430	318	25	1836	83	1	0	0	3	18	0
1985	1561	31	34	1312	59	0	0	0	11	0	10
1986	1368	144	1	1256	0	0	0	29	8	0	0
1987	3073	530	91	1549	0	0	0	34	33	22	0
1988	1406	2141	199	1411	0	0	0	8	7	0	0
1989	2096	3422	315	1173	0	1	0	34	24	0	20
1990	2270	2984	62	627	0	45	0	24	10	0	15
1991	1685	1990	381	167	0	22	0	52	8	1	0
1992	1862	2001	312	51	0	102	0	16	13	30	0
1993	1940	3598	138	179	0	0	0	18	22	0	0
1994	2551	4380	754	185	0	0	0	54	10	1	0
1995	4939	4156	656	53	0	0	0	33	31	0	12
1996	2041	3558	1748	0	0	0	0	126	28	0	0
1997	409	5867	1039	38	0	207	0	85	69	0	2
1998	0	7317	2019	10	0	541	0	150	20	0	172
1999	0	7673	2020	77	0	650	0	132	10	0	91
2000	0	5559	1793	0	0	493	0	135	36	0	198
2001	0	3877	1124	14	0	389	0	32	36	0	53
2002	75	1226	2040	0	0	482	0	30	0	0	271
Total	**63894**	**64767**	**16140**	**52961**	**5093**	**2943**	**1086**	**1025**	**676**	**552**	**937**
Percent	**30.4**	**30.8**	**7.7**	**25.2**	**2.4**	**1.4**	**0.5**	**0.5**	**0.3**	**0.3**	**0.5**

Table 3. Type of Shell Steel of Pressure Tank Cars by Year of Manufacture

Year	Not known	ASTM A516 Gr 70	AAR TC128 GrB	ASTM A515 Gr 70	ASTM A285 Gr C	A516 Gr 70 & TC128	ASTM A212 Gr B	ASTM A240 T316L	ASTM A240 T304L	A515 Gr 70 & TC128	Other
1956	2	0	0	0	0	0	0	0	0	0	0
1957	2	0	0	0	0	0	0	0	0	0	0
1958	0	0	0	0	2	0	0	0	0	0	0
1959	0	0	0	0	0	0	0	0	0	0	0
1960	0	0	0	0	0	0	0	0	0	0	0
1961	0	0	0	0	0	0	0	0	0	0	0
1962	1	0	0	0	0	0	0	0	0	0	0
1963	174	0	1	0	6	0	338	0	0	0	0
1964	382	0	3	1	21	0	439	0	0	0	25
1965	309	0	154	0	13	0	418	0	0	0	60
1966	543	0	1045	7	3	0	230	0	0	0	6
1967	558	6	1347	5	12	0	23	0	0	0	0
1968	398	14	1404	38	9	0	2	0	0	0	0
1969	783	4	1653	8	4	0	4	0	0	0	3
1970	599	9	1635	20	10	0	14	0	0	0	4
1971	429	1	806	0	1	0	2	0	0	0	8
1972	282	5	238	35	0	0	0	0	0	0	0
1973	306	0	791	0	2	0	0	0	0	0	0
1974	392	24	772	0	0	0	0	1	1	0	1
1975	267	9	949	71	2	0	0	0	6	0	13
1976	530	0	868	6	1	0	0	0	0	0	0
1977	838	0	1145	0	2	0	0	0	0	1	0
1978	554	33	1370	0	2	0	0	0	0	0	9
1979	623	8	1408	0	7	0	0	0	0	0	0
1980	785	8	2068	1	8	0	19	0	0	0	4
1981	597	0	1353	6	0	0	0	0	0	0	10
1982	446	0	364	0	0	0	0	0	0	0	0
1983	23	20	61	0	2	0	0	0	0	0	0
1984	109	0	137	0	0	0	0	0	0	0	0
1985	96	0	222	0	0	0	0	0	0	0	0
1986	42	15	195	0	1	0	0	0	0	0	0
1987	40	32	391	0	0	0	0	0	0	0	0
1988	109	4	1071	0	0	0	0	0	0	0	0
1989	72	8	761	0	0	0	0	0	0	0	5
1990	368	48	867	0	0	0	0	0	0	0	0
1991	396	0	1106	0	0	0	0	0	0	0	0
1992	399	5	947	0	0	0	0	0	0	0	0
1993	48	45	831	0	0	0	0	0	0	0	12
1994	213	0	744	0	0	0	0	0	0	0	0
1995	822	0	1456	0	0	0	0	0	0	0	22
1996	389	105	3354	0	0	0	0	0	0	0	72
1997	70	0	2067	0	0	0	0	0	0	0	23
1998	0	26	2635	0	0	0	0	0	7	0	13
1999	0	43	1764	0	0	0	0	0	15	0	10
2000	0	49	1994	0	0	0	0	0	0	0	8
2001	0	59	1692	0	0	0	0	0	0	0	2
2002	0	17	1278	0	0	0	0	0	0	0	0
Total	**12996**	**597**	**42947**	**198**	**108**	**0**	**1489**	**1**	**29**	**1**	**310**
Percent	**22.2**	**1.0**	**73.2**	**0.3**	**0.2**	**0.00**	**2.5**	**0.0**	**0.1**	**0.0**	**0.5**

2.2 The Operating Environment

Table 4 lists the 58 locations of major hump yards in North America [3]. Some locations have more than one yard, so the total is greater than 58 yards. The table identifies the yard name, its operator and location, and the absolute minimum temperature for that location, the lowest temperature expected for two years in ten for U.S. locations [4], and the average low temperature for January [4, 5]. The table is sorted in order of increasing absolute minimum temperature.

From these data, very roughly, a temperature lower than –13°F (–25°C) is expected at least two years in ten in locations north of about 39° of latitude, a line that passes roughly through Baltimore, Cincinnati, Kansas City and Denver, then north of Sacramento.

The number of hump yards has been dropping steadily, as railroads have merged and rationalized their networks, and as freight has shifted from rail to intermodal service. There were 152 hump yards in 1975, which dropped to 122 in 1985, 72 in 1993, then to the 58 active in 2002 [3].

Table 4. Location and Temperatures of Major Hump Yards in North America

Yard	Railroad	Location	State/ Prov	Lat (deg)	Elev (ft)	Temperature (deg F)		
						Abs Min	2 yrs in 10 <	Avg Min
Walker	CN	Edmonton	AB	53.57	2192	-51		1
Symington	CN	Winnipeg	MB	49.88	784	-49		-10
Alyth	CP	Calgary	AB	51.10	3533	-49		4
Weston	CP	Winnipeg	MB	49.88	784	-49		-10
Northtown	BNSF	Minneapolis	MN	44.98	812	-39	-31	-1
St. Paul	CP-Soo	St. Paul	MN	44.94	703	-39	-31	-1
Bailey	UP	North Platte	NE	41.12	2800	-34	-24	9
Kirk	EJ&E	Gary	IN	41.59	600	-29	-19	15
Selkirk	CSX	Albany	NY	42.65	285	-28	-20	11
Gateway	A&S (UP)	East St. Louis	IL	38.62	405	-27	-14	20
Clearing	Belt Rwy Co	Chicago	IL	41.85	596	-27	-19	13
MacMillan	CN	Toronto	ON	43.68	367	-27		18
Agincourt	CP	Toronto	ON	43.68	367	-27		18
Bensenville	CP	Bensenville	IL	41.96	596	-27	-19	13
Blue Island	Indiana H. Belt	Chicago	IL	41.85	596	-27	-19	13
Madison	TRA	East St Louis	IL	38.62	405	-27	-14	20
Proviso	UP	Chicago	IL	41.85	596	-27	-19	13
Galesburg	BNSF	Galesburg	IL	40.95	773	-25	-19	12
Neff	UP	Kansas City	MO	39.10	882	-25	-15	18
Avon	CSX	Indianapolis	IN	39.72	797	-24	-14	17
Elkhart	NS	Elkhart	IN	41.68	750	-24	-17	15
Argentine	BNSF	Kansas City	KS	39.11	740	-22	-14	18
Buckeye	NS	Columbus	OH	40.00	815	-22	-14	19
Frontier	CSX	Buffalo	NY	42.90	215	-20	-10	16
Osborn	CSX	Louisville	KY	38.25	761	-20	-9	23
Queensgate	CSX	Cincinnati	OH	39.16	683	-20	-10	21
Stanley	CSX	Toledo	OH	41.66	174	-20	-14	15
Willard	CSX	Willard	OH	41.05	967	-18	-14	16
Bellevue	NS	Bellevue	OH	41.27	750	-18	-14	16
Conway	NS	Pittsburgh	PA	39.95	770	-18	-13	18
Cumberland	CSX	Cumberland	MD	39.39	730	-17	-6	22
Radnor	CSX	Nashville	TN	36.17	1160	-17	-6	26
Hinkle	UP	Hermiston	OR	45.84	457	-17	-10	26
DeButts	NS	Chattanooga	TN	35.04	682	-16	-3	26
Cherokee	BNSF	Tulsa	OK	36.18	650	-14	-5	34
Tennessee	BNSF	Memphis	TN	35.15	254	-13	2	30
Allentown	NS	Allentown	PA	40.36	399	-12	-6	19
Shaffers Cr'g	NS	Roanoke	VA	37.27	940	-11	-2	25
Sheffield	NS	Sheffield	AL	34.77	550	-11	0	29
Pavonia	Conrail	Camden	NJ	39.77	150	-9	-3	21
Tilford	CSX	Atlanta	GA	33.66	1026	-9	3	29
Pasco	BNSF	Pasco	WA	46.24	383	-8	-3	27
Oak Island	Conrail	Newark	NJ	40.39	80	-8	1	23
Boyles	CSX	Birmingham	AL	33.56	644	-6	4	32
Hamlet	CSX	Hamlet	NC	34.53	300	-6	6	28
Brosnan	NS	Macon	GA	32.84	400	-6	7	34
Norris	NS	Birmingham	AL	33.56	644	-6	4	32
Spencer	NS	Linwood	NC	35.75	659	-6	2	28
Centennial	UP	Fort Worth	TX	32.73	612	-6	5	30

Table 4. (continued)

Yard	Railroad	Location	State/ Prov	Lat (deg)	Elev (ft)	Temperature (deg F)		
						Abs Min	2 yrs in 10 <	Avg Min
N. Little Rock	UP	N. Little Rock	AR	34.77	280	-4	3	29
Norfolk	NS	Norfolk	VA	36.88	26	-3	10	31
Pine Bluff	UP	Pine Bluff	AR	34.20	206	-1	6	31
Rice	CSX	Waycross	GA	31.21	135	3	13	38
Barstow	BNSF	Barstow	CA	34.11	2105	5	15	18
Englewood	UP	Houston	TX	29.76	38	7	16	41
Livonia	UP	Livonia	LA	30.57	45	8	15	37
Davis	UP	Roseville	CA	38.58	20	16	22	38
West Colton	UP	Colton	CA	34.07	1000	21	24	40

3.0 REVIEW OF ACCIDENTS AND FAILURES

3.1 United States

The intent of this review was to identify incidents in which a high-speed coupling impact or a brittle fracture was suspected as a causal factor in damage to a tank car. Accidents such as derailments were excluded from this study. Reports and data were reviewed for evidence of impact-induced brittle failure, especially if a low temperature may have been suspected as a contributing factor to the failure.

3.1.1 Industry Input

At the outset of this project, SwRI solicited information from the tank car industry via a global e-mail and a number of announcements at AAR Tank Car Committee meetings. In particular, we were looking for specific information on accidents or failures that were found to be caused by an impact event. While we were able to locate and obtain many references and material from the AAR, NTSB and FRA websites, no information or experience regarding low temperature impact accidents or failures was provided to SwRI on this project by the tank car builders or owners. Discussions with FRA engineers also referred us to the AAR and NTSB reports.

Therefore, the results and discussion presented herein are derived from publicly available information and reports and do not reflect the experiences of individual tank car builders or owners as such information was not made available.

3.1.2 Accident Databases

3.1.2.1 *RPI-AAR Accident Database*

The RPI-AAR Tank Car Safety Research and Test Project (referred to hereinafter as the "Safety Project") maintains a database of tank car accidents and failures spanning a wide range of conditions and scenarios [6]. Working with the Safety Project, SwRI obtained a subset of this database relevant to the goals of this project*. Specifically, this subset of the RPI-AAR Accident Database contained 554 accidents that were categorized as yard collisions (impacts) that occurred below 50°F. This dataset includes events from 1965 through November 2000 and is listed in Appendix A along with definitions of the codes used to characterize the accidents. The discussion that follows pertains only to this subset of the overall RPI-AAR Accident Database.

The primary purpose of examining this database was to identify the range of speeds and the range of (low) temperatures over which yard impact accidents have been documented. Histogram plots showing the number of yard impact accidents as a function of speed and temperature are shown in Figures 2 and 3, respectively. Note that an "accident" entry in the database is equivalent to a single tank car. Therefore, a single yard impact event that involves five tank cars for example, would result in five separate accident entries in the database.

---

* The RPI-AAR Accident Database is actually maintained by Sims Professional Engineers, Highland, IN, under contract to the Safety Project. The assistance of Mr. Joe Hughes of Sims Professional Engineers is acknowledged in sorting the extensive data contained in the database for the benefit of the low temperature impact project.

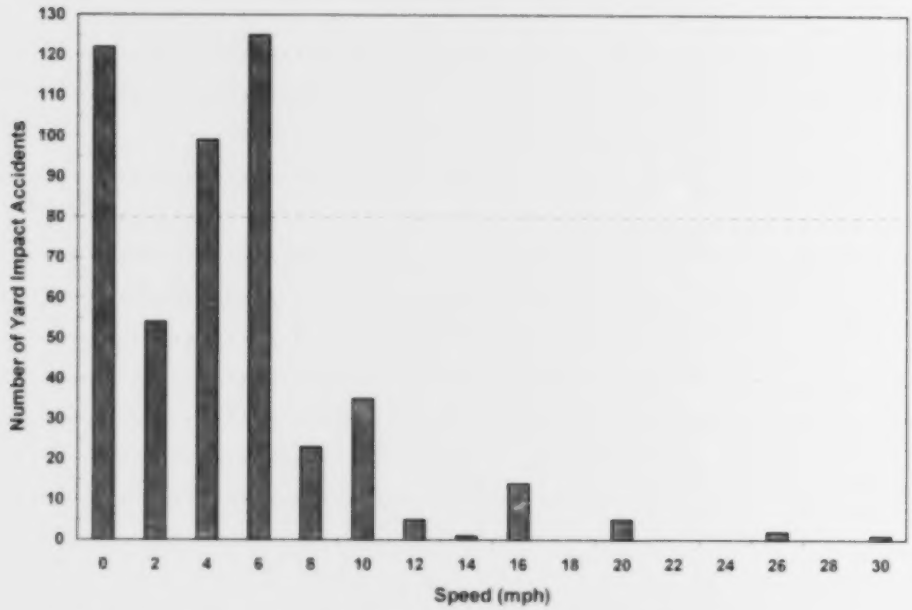


Figure 2. Number of Yard Impact Accidents as a Function of Speed at Temperatures Less than 50°F [6]

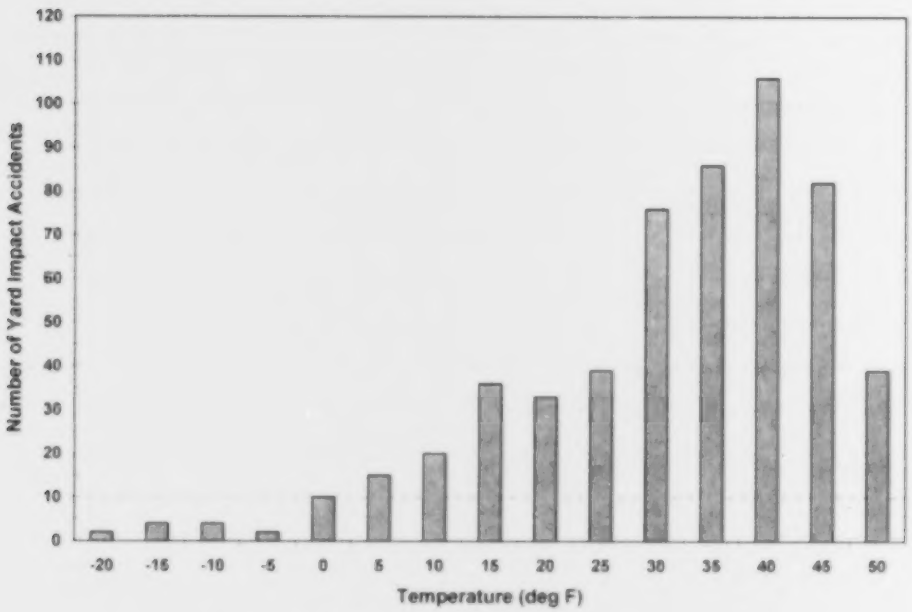


Figure 3. Number of Yard Impact Events as a Function of Temperature [6]

Examining Figure 2, one can see that about 22 percent of the accidents in the database are listed with a zero speed. Presumably, these cars were at rest when impacted by other cars (not tank cars?) or were found to be damaged while at rest subsequent to a suspected earlier (undocumented) yard impact event. The data in the plot are "binned" in 2 mph increments, i.e., the 2 mph bar sums the 1 mph and 2 mph events.

Note also that about 10 percent of the accidents contained in the database are listed with an unknown speed and are not shown on this plot (these 58 accidents are coded with a speed of –99 in the database, see Appendix A). In addition, there are some data that are listed at very high speeds (near 50 mph) that are indeed puzzling from the point of view of what speeds are typical of yard operations. These data are not plotted in Figure 2.

The lowest temperature yard impact event contained in the database is –22°F and the temperature data are plotted in 5°F increments in Figure 3. All of the entries in the database have known temperatures. These data appear to approach a normal distribution (if data at temperatures greater than 50°F were included) and should be compared to the variations in ambient temperature across North America.

Yard impact speeds are plotted against temperature in Figure 4 for those data sets that had known speeds. As expected, there is not an obvious correlation here since impact speed and ambient temperature are really independent variables.

Distributions such as those shown in Figures 2 and 3 can be used in a probabilistic assessment of the risk of low temperature impact failures since the mode of fracture is temperature dependent (ductile or brittle) and the loading is a function of the impact speed. However, it would be more accurate to use site-specific climatological data in place of Figure 3 since a yard in the northern United States would certainly have different mean and standard deviations in ambient temperature than a yard in northern Canada.

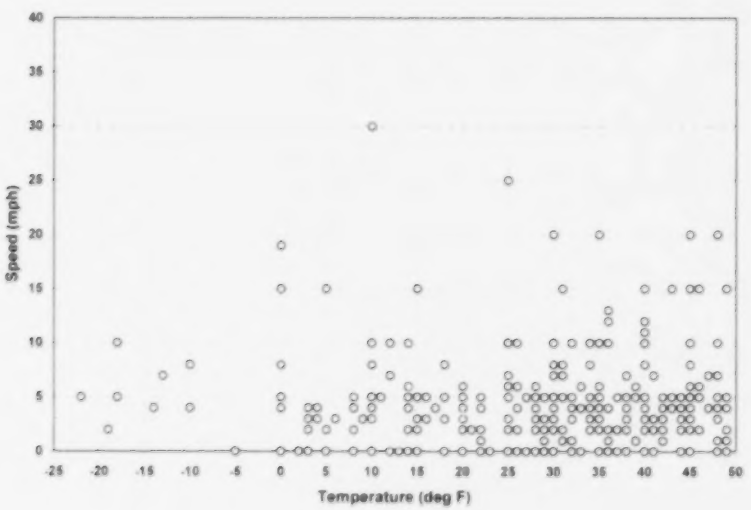


Figure 4. Yard Impact Speed vs. Temperature [6]

3.1.2.2 *Volpe Center Analysis of Tank Car Accident Data*

In 1991, the Volpe National Transportation Systems Center published a report that presented the results of a study of accidents involving railroad tank cars for the years 1981 through 1985 [7]. These analyses were based on a combination of data obtained from the Railroad Accident Incident Reporting System (RAIRS) and Universal Machine Language Equipment Register (UMLER) databases. Results were presented in tabular form for many categories, i.e., accident causes, type of track, temperatures at time of accident, speed at time of accident, etc.

For the purposes of this project, it was hoped that the data compiled in this Volpe report could be accessed to potentially provide additional insight beyond what was obtained from the RPI-AAR Accident Database described in Section 3.1.2.1. Unfortunately, after contacting engineers at the Volpe Center, it was found that little or no information is currently available on the database that was compiled and analyzed for this analysis and the originating author has passed away. Therefore, it was not possible from this report to distinguish yard impact accidents (by temperature and speed) from other accidents. Nevertheless, it is probably reasonable to assume that the accident data contained in Ref. [7] are a subset of those contained in the RPI-AAR Accident Database [6], albeit presented in a different format.

3.1.3 Documented "Brittle" Fractures

While the above referenced RPI-AAR Accident Database contains an enormous amount of descriptive accident data, it does not document the type of failure that occurred in terms of ductile or brittle fractures. In 1998, the Safety Project issued a research report addressing the analysis of the fracture behavior of tank car steels in accidents during the period spanning the years 1981 to 1994 [8]. This Safety Project report also summarized two previous studies conducted in the early 1980s covering tank car accidents and provided an excellent review of the history of the evolution of the steel specifications used in tank cars.

Ref. [8] identified 13 fracture cases that were characterized as brittle fractures, eight of which occurred during yard impacts. Table 5 provides a list of these eight specific yard impact events, all of which are contained in the RPI-AAR Accident Database discussed in Section 3.1.2.1. The information in Table 5 was taken from the table in Appendix A of Ref. [8], augmented with additional data found elsewhere in that report. Note that in each of the cases where the minimum NDT was reported, the ambient temperature at the time of the accident was below the NDT.

The yard impact events listed in Table 5 exhibited cracks or failures exceeding 18 in. in length. This is due to the fact that the technique used to distinguish between brittle and ductile fracture cases in Ref. [8] was based on earlier work by Pellini [9] that considered punctures or fractures smaller than 18 in. long to be ductile because of the lack of extensive crack propagation.

Table 5. Yard Impact Accidents (from 1981 to 1994) Characterized as Brittle Fractures in Ref. [8]

Ref. [8] Case	Car	Year Built	Pressure Car	Speed (mph)	Tank Material	Accident Date	Accident Location	Ambient Temp (°F)	Minimum NDT (°F)	Failure Location
1	ACFX 12405	64	NO	5	A212B	21-Jan-1985	Conway, PA	-22	20	shell
2	ACFX 14702	60	NO	19	A285C	11-Feb-1982	Toledo, OH	0	20	shell
4	GATX 1037	65	NO	NR	A212B	10-Feb-1994	Buffalo, NY	10	20	head
5	GATX 24164	55	NO	10	A285C	8-Feb-1984	Chicago/Clearing Yard, IL	26	NR	shell
7	PROX 47917	69	NO	NR	A285C	27-Jan-1994	Montreal/Taschereau Yard, QC	-22	0	sill/head/shell
9	PSBX 33104	64	YES	0*	A212B	13-Dec-1982	Winnipeg, MB	15	20	head
10	UTLX 567	69	NO	7	A285C	21-Dec-1983	Calgary, AB	-13	20	head
13	UTLX 98646	80	YES	2	TC128B	28-Feb-1984	Toronto, ON	14	NR	head

NR = Not Reported

*Car was stationary; struck by 6 runaway locomotives at 35 mph.

It is important to note that Ref. [8] includes accidents only from 1981 through 1994. A previous Safety Project effort [9] reviewed and documented accidents resulting in 19 brittle failures over the period from 1965 to 1980. The RPI-AAR Accident Database (Appendix A) also contains 66 entries covering the period from 1995 to 2000 (categorized as yard impacts at temperatures less than 50°F). For example, the well-known Selkirk, NY, low temperature yard impact accident, in which the brittleness of the tank steel was concluded by the NTSB to be a contributing factor [10], occurred in March 1996 and is one of these more recent events. As of this writing, however, it is unknown if any of these other yard impact accidents exhibited a brittle fracture.

3.2 Canada

A literature search was made to collect published data on tank car accidents that occurred in Canada in the past 40 years. The best sources found were in the files of the Canadian government regulatory bodies, which had regulatory responsibilities for the Canadian railways. Over the years, these were the Canadian Board of Transport Commissioners, the Canadian Transport Commission (CTC), the National Transportation Agency, and currently, the Transportation Safety Board of Canada (TSB) and Transport Canada. Much support was received from the TSB Engineering Laboratory, the TSB library, and the Transport Dangerous Goods Directorate of Transport Canada, which had file copies of some of the earlier tank car failure reports.

A total of 31 incidents dating from 1982 were identified in which accidental tank car failures occurred, leading to product release. Table B-1 in Appendix B shows the Canadian tank car accident history and damage profile. The table assigns a record ID number in the first column. Figure 5 shows a Venn diagram of tank car accidents. The outer circle encompasses all 31 accidents. Of the 31 accidents, 11 were related to train derailment, and a subset of 20 may be considered related to coupling or abnormal coupler force events at any temperature. These are ID numbers 1 to 10, 12 and 13, 15 to 19, 25, 27, and 31. The subset of coupling events that are known to be related to low temperature (< 32°F) are the six with record ID numbers 1, 2, 5, 8, 9, and 31.

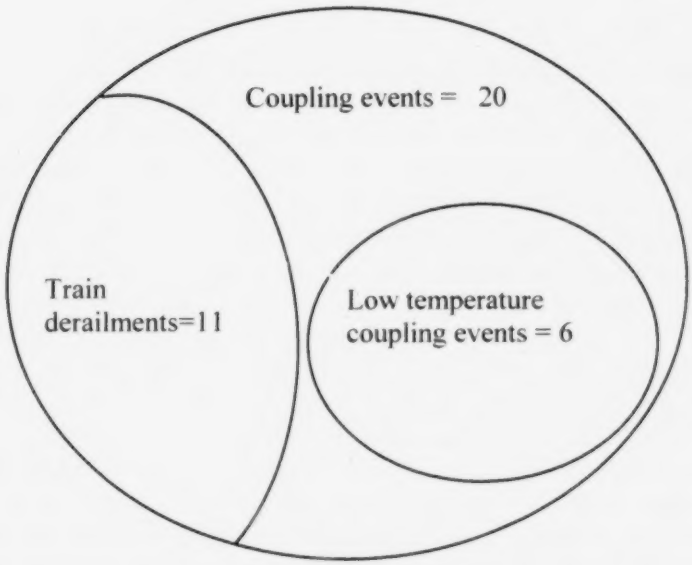


Figure 5. Venn Diagram of Tank Car Accidents in which Tank Car Failure Released Product

Table B-1 shows that, where the built date is known, the car was built prior to 1974 in all but two of the accidents. One derailment involved cars built in 1997, and another failure involved a car built in 1974. Three of the six low temperature coupling events occurred on cars built in or before 1970. The built dates of the other three cars are not known.

In reviewing all 31 accidents, including the derailments, 14 involve CTC/DOT 111 cars, 5 involve CTC/DOT 112 cars, and the car specification is unknown in the remaining 11. Two of the six low temperature coupling events involve CTC/DOT 111A specification cars, a third is a CTC 112J specification at the time of the incident after several changes and modifications since it was built in 1966, and the car specification is unknown in the remaining three.

Table 1 shows that CTC/DOT 111 non-pressure cars make up about 78 percent of the tank car fleet, and the balance is mostly CTC/DOT 105/112 pressure cars. The above two breakdowns of accidents are roughly consistent with the proportions of these car specifications in the population.

3.3 Bibliography of Accident Reports

A listing of all the accident reports obtained and reviewed by SwRI on this project is contained in Appendix C. Material data from these reports (if available) are discussed in Section 5.0.

4.0 THE ROLE OF DRAFT GEAR IN TANK CAR COUPLING IMPACT

4.1 Introduction

Rail cars are fitted with draft gear at each end to cushion the draft and buff forces transmitted between cars in train movements and to provide for the absorption of kinetic energy during car couplings and from in train forces. In the case of stub sill tank cars, the draft gear is applied in the 24 5/8 in. standard draft gear pocket length inside the end of the stub sill. The draft and buff lugs then transfer the coupling loads to the tank structure via the stub sill and its attachments to the tank. The alternate standard 36 in. draft gear pocket length is also used, but generally on long cars where the sill length and car body overhang outside the car bolsters are greater. The 36 in. draft gear pocket can accommodate draft gears with higher energy capacity rating. However, most stub sill tank cars use the 24 5/8 in. pocket length.

4.2 Draft Gear Specifications

AAR Specification M901 [11] in the AAR Manual of Standards and Recommended Practices provides the specifications for draft gear that will be accepted in North American Railway Interchange service. The evolution of draft gear cushioning capacity has historically followed AAR Specification M901, which has been revised and re-adopted several times over the years since its first adoption in 1931. These revisions have generally provided an increase in draft gear cushioning capacity over the years, as necessitated by the various increases in gross rail load. The specification is currently up to M 901K-00 for hydraulic draft gear rating. Most of the stub sill tank car fleet is likely to have friction or friction/elastomeric draft gear meeting at least AAR M901E-59 or later revisions.

Early tank cars were constructed using a continuous "through center sill" below the tank to support the loaded tank inertial and coupling forces. Union Tank and Procor undertook prototyping work in 1957 to develop the stub sill concept to reduce the tare weight of tank cars. Production quantities of stub sill tank cars were entered into revenue interchange service from 1963 onwards.

4.2.1 AAR Specification M901E

In M901E-00, the draft gear capsule is rated in terms of the energy absorbed at a **rated force** and a **rated stroke** ("Official Rating Travel"). The **rated force** is set at a compression force of 500,000 lbf, and the **rated stroke** is the initial compression stroke at which the rated force level is achieved. The draft gear is then assigned a **rated energy** ("Official Rating Travel") capacity in foot-pounds, based on the area under the rated force-rated stroke curve. The rated energy capacity is usually less than the "Official Maximum Travel" energy capacity of the draft gear, as over travel beyond the rated stroke to "Official Maximum Travel" condition will allow more energy absorption. The "Official Maximum Travel" is that stroke at which 800,000 lbf buff reaction occurs. The

over travel stroke to "Official Maximum Travel" condition is usually not very much greater than the rated stroke. Three inches would typically represent the rated stroke and 3¼ in. the "Official Maximum Travel" stroke for a gear with rated energy of order 40,000 ft.-lb., and solid energy capacity of order 50,000 ft.-lb. If the input energy level exceeds the "Official Maximum Travel" capacity energy level, then draft gear reaction force rises rapidly beyond the solid stroke level, and depends primarily on the stiffness of the reaction structure, the weights of the cars, and the residual velocity when solid stroke was achieved.

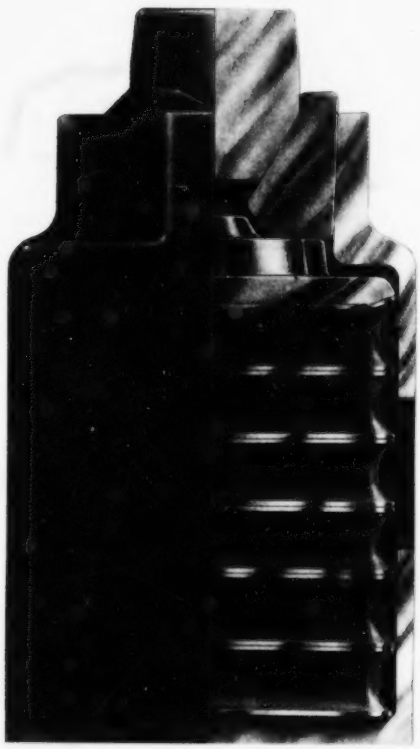
Detailed testing procedures and requirements for rating draft gear are given in the specification [11]. The rating test is usually carried out in a draft gear manufacturer's testing laboratory facility using a Tup Testing machine, in which a 27,000 lb. drop hammer is raised sequentially to incrementally increasing heights, and released in free fall onto the test draft gear capsule, which is supported on a load cell platen below the Tup weight. The draft gear absorbs the kinetic energy of the falling drop hammer. Precision time history measurements of gear stroke, gear reaction force, and Tup drop height are recorded, for drop heights increased in ¼ in. increments, until the 500,000 lb. peak reaction rating force is reached or exceeded. Gear energy rating, rebound energy, "Official Maximum Travel" stroke and energy are all recorded, and the gear is assigned an AAR energy rating in accordance with AAR specification M901E-00.

4.2.2 Draft Gear Energy Absorption

End-of-sill pocket draft gear designs in use in the early 1960s and 1970s (and still in use today), which were rated under M901E, were usually characterized as either a friction gear using steel spring preloaded friction clutches (wedges) to absorb and dissipate energy, an elastomeric (rubber) spring with hysteretic material energy absorption, or a combination of both friction clutches and elastomeric preload springs.

Figure 6, from a Miner Enterprises Inc. technical document describing the Miner SL-76 draft gear, shows a cutaway view of a Miner friction/rubber draft gear. The friction clutch (wedge) mechanism can be clearly seen, and the pre-loading return spring is made up of a set of bonded rubber pad spring elements operating in series. Energy is dissipated by the friction wedge mechanism as well as in the hysteresis of the elastomeric spring material.

Similarly, Figure 7 shows a cutaway view of the interior of an all steel friction clutch draft gear, clearly showing the series of friction wedge surfaces which slide relative to each other, under normal load produced by the steel return spring and preload as the gear is compressed. The energy absorbed is dependent on the cumulative relative sliding distance of the friction wedge surfaces, the normal forces between the wedge elements, the friction coefficient on the wedge surfaces, the return spring stiffness, and the static preload. Most of the total energy absorbed on the initial compression stroke is dissipated in friction heating, but a small amount, the rebound energy, is returned as kinetic energy to the cars, on draft gear expansion.



Performance Specifications	
Official rating travel-inches	3.05
Official capacity-foot pounds	47,820
Reaction force @ rating travel, lbs.	511,000
Ratio of reaction force to capacity pounds per foot-pounds	10.69
Gear weight–lbs.	314
Maximum capacity of 53,900 ft. lbs. at 3.15 inches of travel and 851,000 lbs. reaction force	

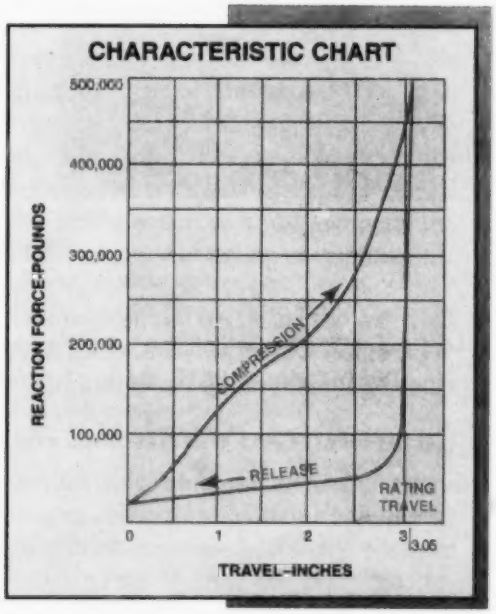
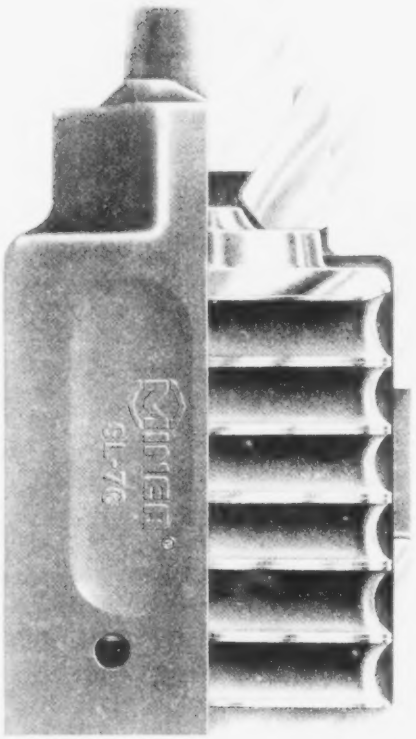


Figure 6. Cutaway View of the Miner SL-76 Friction/Rubber Draft Gear, M901E Rating Specification, and Reaction Force-Travel Curve



Performance Specifications	
Official rating travel-inches	3.05
Official capacity-foot pounds	47,820
Reaction force @ rating travel, lbs	511,000
Ratio of reaction force to capacity pounds per foot-pounds	10.69
Gear weight-lbs	314
Maximum capacity of 53,900 ft. lbs. at 3.15 inches of travel and 851,000 lbs. reaction force	

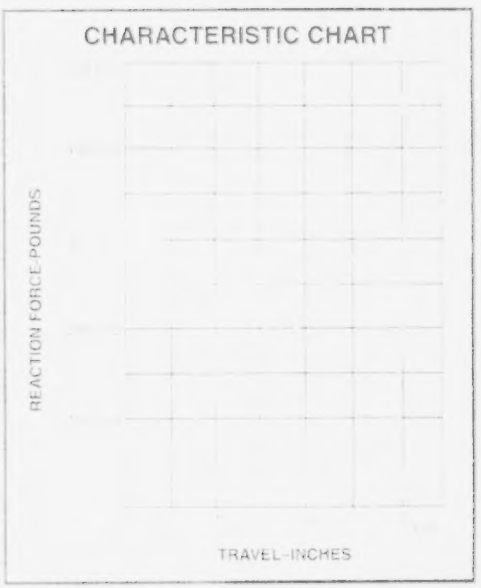
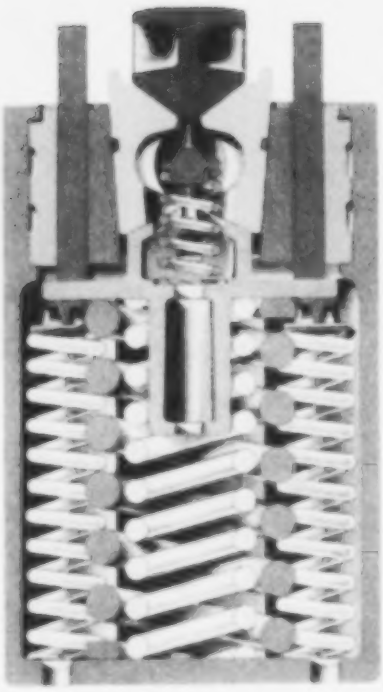


Figure 6. Cutaway View of the Miner SL-76 Friction Rubber Draft Gear, M901E Rating Specification, and Reaction Force-Travel Curve



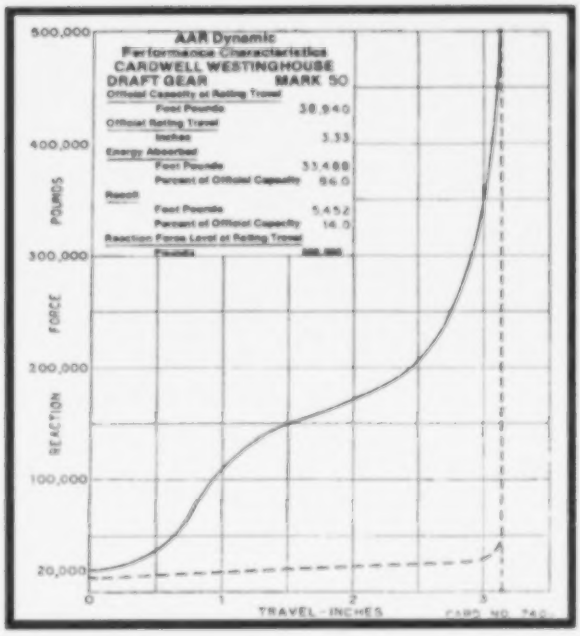


Figure 7. Cutaway View of a Cardwell-Westinghouse Mark 50 All Steel Friction Draft Gear, M901E Rating Specification, and Reaction Force-Travel Curve

This Draft Gear was Accepted and Certified in 1961 Under AAR M901E (1959).

4.2.3 Certification Temperature Requirements and Low Temperature Laboratory Tests

AAR Draft Gear Specification M901 neither provides a low temperature test specification, nor requires a low temperature test qualification. M 901E-00 (Section 6.1) does require that the test laboratory be in a building having uniform temperature, that the test draft gears be kept there for at least 24 hours prior to testing, and that the friction surfaces be protected from moisture, grease, dust, etc. M901G-00 (Section 6.4) defines a range of impact ramp ambient temperature between +20°F and +90°F "to minimize the effect of varying atmospheric conditions". As well, M901G-00 (Section 7.1) requires the same conditions as section 6.4 of M901E-00 for the drop hammer testing. The low temperature energy absorption performance of the draft gears (i.e., operation below the range from 0°F to –40°F ambient temperature) **is currently not a specified requirement**. A temperature of +20°F is not considered a seriously low temperature for purposes of this study.

Both Cardwell-Westinghouse and Miner Enterprises Inc. have low temperature cooling boxes suitable for chilling draft gear to –40°F prior to drop hammer capacity tests. The main problem with these laboratory tests is that serious frosting occurs on the chilled draft gear, and its friction surfaces, due to ambient humidity in the test room. This happens both during transfer of the test draft gear from the cold box to the drop hammer, and during the series of drops required to determine capacity at the rated force level. Since these draft gear rely on repeatable friction characteristics between the surfaces of the sliding components, frost contamination may give a distorted energy capacity and stroke rating, when compared to draft gear capacity performance in a low temperature, but low ambient humidity (possibly relatively frost free) revenue coupling environment.

Cardwell-Westinghouse has attempted to mitigate this problem by enclosing the test draft gear in a dry nitrogen atmosphere within a heavy gauge plastic bag, which works, but only for the first drop hammer blow. The first blow ruptures the bag, and frosting occurs during the subsequent hammer drops.

Cardwell-Westinghouse has provided some experimental insight into the low temperature effect. Tests on four different types of draft gear were carried out as described above, where the first drop hammer blow occurred with the draft gear inside the dry nitrogen atmosphere in the sealed plastic bag. The bag was then resealed and the draft gear re-chilled, but dry-out conditions were not controlled, i.e. the draft gear was not brought up to room temperature for a period of time to dry out surface condensation, then re-sealed and re-chilled, as this would be about a 24 hour cycle. Figure 8 shows the results observed from these tests. The data graph provided shows peak reaction forces measured at AAR Draft Gear rated capacity for Cardwell-Westinghouse friction draft gears that use either steel coil springs (Mark 50 model) or a combination of steel coil springs and rubber spring elements to load the friction surfaces (Mark R-500 model), as well as for two friction draft gear models that use only elastomeric spring materials. These two models are not further identified.

Figure 8. Draft Gear Buff Peak Reaction Force at Rated Travel Input at Four Test Temperatures (ambient, 0°F, –20°F, and –40°F)

The all steel draft gear shows a modest decrease in peak reaction force at rated travel with test temperature variation from ambient to –40°F. The Cardwell-Westinghouse Mark 50 model reduced its peak buff reaction force from 420,000 lb. to 310,000 lb. The result observed may suffer from ice contamination due to uncontrolled dry-out conditions. The rated force level of 500,000 lb. was not achieved, and the forces reported are those at rated stroke level, before the draft gear went solid.

The steel coil spring and rubber spring combination draft gear, Cardwell-Westinghouse Mark R-500 model, showed an increase in peak reaction force at rated travel between

ambient and –40°F, with peak force rising from 500,000 lb. to 580,000 lb. The elastomeric spring friction draft gear model No. 1 showed a significant increase in peak reaction force at rated travel between ambient and –40°F, with peak force rising from 525,000 lb. to 780,000 lb., respectively.

Cardwell-Westinghouse felt that the increasing peak buff reaction forces, with decreasing temperature, for the gears equipped with rubber or elastomeric springs, were caused by increasing stiffness of the elastomer with decreasing temperature.

Full-scale exploratory coupling impact tests were undertaken by NRC-CSTT using the Cardwell-Westinghouse Mark 50 draft gear to see whether similar trend results were observed. These are described in Section 4.4 of this report.

4.2.4 Draft Gear Reconditioning Requirements

AAR draft gear Specification M 901B-00 gives the requirements for approving secondhand and reconditioned draft gears for freight service. M901B-00, Section 3.1, requires that draft gear exceeding 16 years from date of manufacture, or 10 years from date of last reconditioning, must be recertified or scrapped. Cardwell-Westinghouse advised that in their experience, the majority of friction draft gears submitted for recertification or reconditioning are not completely worn out, but still retain a significant percentage of their original cushioning and energy absorption characteristics. They may have been removed from service due to mechanical wear limits on friction surfaces or age limits being attained. A few used draft gear do have internally damaged components or damaged housings, requiring the unit to either be rebuilt or scrapped.

Miner Enterprises Inc. has provided data shown in Figure 9 on the Miner model SL-76 friction/rubber draft gear after eight years in revenue unit coal train service and over one million revenue service car miles. Note that these draft gear would have fewer cumulative coupling impacts under switching conditions, as unit train cars are less frequently uncoupled from each other, compared to other cars in general freight service.

Official Test Results in Ft./Lbs. for GUAX 82102

Miner SL-76 Draft Gear	Capacity as Received	Capacity at 1.31" Travel	Capacity at 500K Lbs. Reaction Force	Capacity at Max Travel
"A" End Gear	39,800	21,100	39,000	59,900
"B" End Gear	39,600	21,300	41,400	61,600

Both draft gears demonstrated that they were providing *excellent cushioning protection* at the time they were removed from service. The capacity at 1.31" travel indicates strong resistance to closure during "run in/run out" conditions of typical train action. Both gears averaged 60,000 ft. lbs. capacity at maximum travel, demonstrating excellent car protection.

Figure 9. Miner Model SL-76 Measured Draft Gear Capacity after Eight Years and One Million Miles in Revenue Unit Train Coal Service

ambient and –40°F, with peak force rising from 500,000 lb. to 580,000 lb. The elastomeric spring friction draft gear model No. 1 showed a significant increase in peak reaction force at rated travel between ambient and –40°F, with peak force rising from 525,000 lb. to 780,000 lb., respectively.

Cardwell-Westinghouse felt that the increasing peak buff reaction forces, with decreasing temperature, for the gears equipped with rubber or elastomeric springs, were caused by increasing stiffness of the elastomer with decreasing temperature.

Full-scale exploratory coupling impact tests were undertaken by NRC-CSTT using the Cardwell-Westinghouse Mark 50 draft gear to see whether similar trend results were observed. These are described in Section 4.4 of this report.

4.2.4 Draft Gear Reconditioning Requirements

AAR draft gear Specification M 901B-00 gives the requirements for approving secondhand and reconditioned draft gears for freight service. M901B-00, Section 3.1, requires that draft gear exceeding 16 years from date of manufacture, or 10 years from date of last reconditioning, must be recertified or scrapped. Cardwell-Westinghouse advised that in their experience, the majority of friction draft gears submitted for recertification or reconditioning are not completely worn out, but still retain a significant percentage of their original cushioning and energy absorption characteristics. They may have been removed from service due to mechanical wear limits on friction surfaces or age limits being attained. A few used draft gear do have internally damaged components or damaged housings, requiring the unit to either be rebuilt or scrapped.

Miner Enterprises Inc. has provided data shown in Figure 9 on the Miner model SL-76 friction rubber draft gear after eight years in revenue unit coal train service and over one million revenue service car miles. Note that these draft gear would have fewer cumulative coupling impacts under switching conditions, as unit train cars are less frequently uncoupled from each other, compared to other cars in general freight service.

Official Test Results in Ft./Lbs. for GUAX 82102

Miner SL-76 Draft Gear	Capacity as Received	Capacity at 1.31" Travel	Capacity at 500K Lbs Reaction Force	Capacity at Max Travel
A' End Gear	39,800	21,100	39,000	59,900
B' End Gear	39,600	21,300	41,400	61,600

Note: draft gears demonstrated that they were providing excellent cushioning when removed after one million revenue service car miles. The capacity at 1.31" travel includes energy absorbed by gear and car body. The capacity at maximum travel was when B' end gear bottomed out at 3.5" travel. The capacity at maximum travel was approximately equivalent to the AAR requirement.

Figure 9. Miner Model SL-76 Measured Draft Gear Capacity after Eight Years and One Million Miles in Revenue Unit Train Coal Service

Two used draft gear were removed from the same car (GUAX82102, A and B ends) and tested at Miner's facilities under the 27,000 lb. drop hammer. This draft gear, when new, has an AAR M901E-00 certified energy capacity rating of 47,820 ft.-lb. The test results (average capacity of two units at rated force level = 40,000 ft.-lb.) show a loss of original rated energy capacity of the order of 16 percent, but still meet the required minimum energy capacities of AAR Specification M901B-00, paragraph 6.2.3, for tests of non reconditioned draft gear previously rated under M901E-00, or 32,400 ft.-lb. AAR specification M901B-00, paragraph 6.2.4, also requires that **reconditioned** draft gears, rated under M901E-00 must demonstrate **minimum** rated energy capacity of 36,000 ft.-lb. after reconditioning.

4.2.5 AAR Specification M901G

AAR Specification M901G-00 in the AAR Manual of Standards and Recommended Practices was adopted in 1964 and provides for a tighter and performance-related specification under full-scale coupling impacts for friction, elastomeric, or combination type draft gears that will be accepted in North American Railway Interchange service. The specification is based on the Tup testing as in M901E-00, but also has added an **impact velocity rating minimum** as stated in paragraph 9.1.2 of M901G-00 such that **"at no time during the test may the rating be less than 5 mph at 500,000 lbf reaction."** The rating velocity is based on the initial coupling speed of a hammer car impacting a standing anvil car, both cars each to be hopper cars loaded with dry sand (a solid load) to 220,000 lb. gross rail load. This specification is currently followed by car builders for stub sill tank cars being produced today.

4.3 Mathematical Relationships for Coupling Impact

The impact energy analysis for the simple case of coupling two equal weight railcars that are both free to roll, one initially stationary (the anvil car) and one initially moving (the hammer car), is based on the conservation of momentum before and after impact. This is the situation for the **impact velocity rating** test of AAR specification M901G.

Let V_1 = initial velocity of the hammer car
V_2 = initial velocity of the anvil car (= 0 for this test)
V_f = velocity of both cars after the coupling impulse is over
m_1 = mass of hammer car
m_2 = mass of anvil car
g = gravity constant

All in a consistent set of units.

From the conservation of momentum equation,

Momentum before impact = Momentum after impact

$$m_1V_1 + m_2V_2 = (m_1 + m_2)V_f \quad (1)$$

So, $$V_f = \{m_1V_1 + m_2V_2\}/(m_1 + m_2) \quad (2)$$

The system kinetic energy just before impact $= 0.5m_1V_1^2$ (3)

The system kinetic energy just after impact $= 0.5\{m_1 + m_2\}V_f^2$ (4)

The change in kinetic energy during the impact is

$$\text{Kinetic energy change} = \Delta KE = 0.5\{(m_1 + m_2)V_f^2 - m_1V_1^2\} \quad (6)$$

For the case of the AAR M901G **impact velocity rating test**, $m_1 = m_2 = m$, and $V_2 = 0$, the impact equations become

$$V_f = 0.5V_1 \quad (7)$$

$$\Delta KE = -0.25mV_1^2 \quad (8)$$

where ΔKE = the energy absorbed by both draft gears, lading losses, suspensions, etc.

$$\Delta KE = 2 \times \text{Energy Capacity Rating} = 1/4 \times mV_1^2$$

and $V_1 = V_{\text{rated impact velocity}}$

$$V_{\text{rated impact velocity}} = \{(8 \times \text{Energy Capacity Rating})/m\}^{0.5} \quad (9)$$

where energy capacity rating = the rated energy capacity of one draft gear augmented by a factor that accounts for impact energy losses in the lading, suspension, etc.

Equation (7) shows that after impact and coupling, the pair of cars will roll away at one half the initial velocity of the hammer car. Equation (8) shows that 50 percent of the original kinetic energy (initial KE was $0.5mV_1^2$) must be removed from the system (the negative sign represents a loss of KE) during this simple case of coupling impact (AAR M901G impact velocity rating test). Theoretically, if the energy dissipation is shared equally, each draft gear at the point of coupling must absorb 25 percent of the initial kinetic energy of the hammer car. Practically, the car structures, ladings, and suspensions also contribute an additional 10 to 15 percent to the absorption of KE coupling loss. Table 6 shows the **hammer car** kinetic energy for selected car gross rail loads and coupling speeds.

4.3.1 Experimental Confirmation of the Theory

Table 7 shows an estimate, based on equation (9), of the impact velocity rating for various car nominal gross weights and specific draft gear **rated energy capacities**, ranging from the lowest acceptable service worn rated energy level to the current maximum levels available in friction hydraulic-assisted draft gear that fit in the 24 5/8 in. stub sill pocket. These rated energy capacities have been increased by 15 percent to allow for energy loss in the car lading and suspension. **These calculations assume solid lading**. Sloshing, in fluid ladings with tank car outage, will be discussed later, as this can have a significant protective effect.

Table 6. Car Kinetic Energy for Various Speeds and Gross Weights on Rail

GRL (lb)	220,000	263,000	286,000	315,000	100,000
Speed	Kinetic Energy				Tare wt (est)
mph	ft-lb	ft-lb	ft-lb	ft-lb	ft-lb
1.0	7,349	8,785	9,553	10,522	3,340
2.0	29,394	35,139	38,212	42,087	13,361
3.0	66,137	79,063	85,978	94,696	30,062
4.0	117,576	140,557	152,849	168,348	53,444
5.0	183,713	219,620	238,827	263,043	83,506
6.0	264,547	316,253	343,911	378,783	120,248
7.0	360,077	430,456	468,100	515,565	163,671
8.0	470,305	562,228	611,397	673,391	213,775
9.0	595,230	711,570	773,799	852,261	270,559
10.0	734,852	878,482	955,307	1,052,174	334,023

Table 7. Coupling Speeds for Various Draft Gear Energy Ratings and Selected Car Gross Rail Loads

	DG Impact rated Energy capacity	(1.15 x DG Impact Energy rating	Impact Velocity Rating (estimated)[1]				
Notes	ft-lb	ft-lb	mph	mph	mph	mph	mph
[2]	32,400	37,260	4.5	4.1	3.9	3.8	6.7
[3]	36,000	41,400	4.7	4.3	4.2	4.0	7.0
[4]	40,000	46,000	5.0	4.6	4.4	4.2	7.4
[5]	48,000	55,200	5.5	5.0	4.8	4.6	8.1
[6]	67,000	77,050	6.5	5.9	5.7	5.4	9.6

[1] Coupling at velocities above those tabulated will produce peak coupling forces greater than 500,000 lb.

Notes for energy ratings shown

[2] AAR M901B Minimum energy rating (non reconditioned state)
[3] AAR M901B Minimum energy rating (after reconditioning)
[4] AAR M901E Average energy rating (typical service worn 8 years)
[5] AAR M901E New energy rating (typical)
[6] New energy rating high capacity (friction/Hydraulic assist)

It can be seen from Table 7 that draft gear qualified under AAR M901E-00 with an impact energy rating of the order of **48,000 ft.-lb.**, and including an additional 15 percent allowance for car lading, suspension, etc. energy losses, can easily meet the **impact rating velocity** minimum requirements of 5 mph for 220,000 lb. cars. Applying the same draft gear to cars heavier than specified in AAR M901G-00 reduces the impact velocity rating to 5 mph for 263,000 lb. cars. Table 7 also shows that loss of impact energy rating with service wear to 40,000 ft.-lb., as shown in Figure 9, drops the impact velocity rating below 5 mph for cars 263,000 lb. or heavier. Empty cars still have impact velocity ratings exceeding 5 mph, even with significantly reduced energy rated capacity due to wear.

Figure 10 shows test results provided by Cardwell-Westinghouse/Miner Companies of full-scale impact tests as per AAR M901G test procedure for new steel friction draft gears.

The theoretical **impact velocity ratings** calculated in Table 7 and those measured experimentally in Figure 10 both follow the same trend, as shown in Table 8. In both cases, increasing car weight at a given energy rating level (including an additional 15 percent impact energy loss in the car suspensions, etc.) decreases the **impact velocity rating**. The measured impact velocity ratings from the tests yield impact velocity rating results somewhat lower than predicted for the heavier cars.

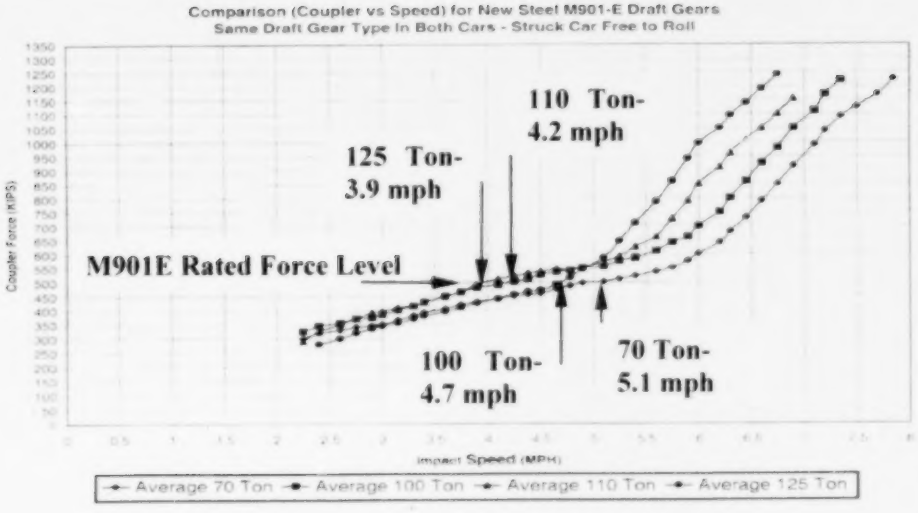


Figure 1 (appB-1) A set of test results provided by Miner/Cardwell/Westinghouse

Figure 10. Impact Velocity Rating Test Results (Average) for New Steel M901E Draft Gears Tested as per M901G for Impact Velocity Rating

Table 8. Comparison of Theoretical and Measured Impact Velocity Ratings for New Steel M901E Draft Gears Tested per M901G

Rated Energy →		41550 ft.-lb.	
Nominal car capacity and Gross Rail Load		Theoretical (mph)	Measured (mph)
tons	lb.		
70	220,000	5.1	5.1
100	263,000	4.7	4.7
110	286,000	4.5	4.2
125	315,000	4.3	3.9

4.3.2 The Consequences of Coupling at Speeds above the Impact Velocity Rating

Coupling at speeds above the **Impact Velocity Rating** will cause the peak buff impact force to exceed the **Rated Force Level** of 500,000 lb. If the hammer car coupling velocity and kinetic energy is sufficient to drive the draft gear solid, the rate of change of the peak buff impact force increases as seen in Figure 10. After the draft gears are compressed to solid condition, the peak impact force is determined by the remaining velocity difference between the hammer and the anvil cars, the sill/car structure stiffness, and the car weights. The peak forces can increase at a much higher rate (typically by a

factor of 4 to 5 times higher) compared to when the draft gears were providing impact cushioning under less than solid stroke conditions.

For the hopper car types (and sill stiffnesses) used in the AAR M901G-00 test results shown in Figure 10, the rate of increase of peak buff coupling force is of an order of 85,000 lb./mph when the draft gear are providing cushioning. This increases to about 350,000 lb./mph after the gears have gone solid. The hammer car transition speed depends on the excess solid capacity and solid travel compared to the rated values.

Railcars used in AAR Interchange service are constructed to AAR Specification M1001 [12], and are able to withstand peak buff forces exceeding 500,000 lb. Cars built in the 1960 – 1974 period were required to withstand a quasi-static squeeze load of 800,000 lb. buff, with no yield. From 1974 onwards, this requirement was raised to 1,250,000 lb. peak buff load, without yield. In Figure 10, for 100-ton cars, the 800,000 lb. level is reached around 5.9 mph for the sill stiffness of a typical hopper car. Coupling beyond this speed may lead to localized car yield at stress concentration points and, if stress concentrations are severe enough, cracks may initiate or grow due to high-strain low-cycle fatigue as a result of over-speed impact couplings. For cars constructed since 1974 to the 1,250,000 lb. buff specification, coupling speeds of the order of 7.5 mph and higher would be needed to reach this peak coupling force level for loaded hopper car structures. Loss of draft gear capacity due to wear, broken internal components, etc. will obviously reduce the peak impact force protection afforded to the cars before a solid draft gear condition is reached, allowing high sill forces to develop at even lower speeds.

The **fatigue endurance stress** for materials always lies below the yield point of the material and would typically be about half the yield stress of the material or higher. The introduction of necessary design and fabrication stress raisers, such as sudden section thickness or geometry changes, heat affected zones at welds, etc., reduces the fatigue endurance stress at these details below the undisturbed material endurance limit. So the increase in stub sill tank car squeeze strength, although favorable from the fatigue loading strength perspective of the stub sill tank car, does not imply that cars can withstand an infinite number of 7.5 mph impacts. These "high stress-low cycle" impacts may represent an area of further investigation to identify their relationship to the low temperature failures of stub sill tank cars.

4.3.3 The Protection Effect of Fluid Loads with Tank Outage

Tank cars are not usually internally fitted with baffles, nor are they ever quite filled to full volumetric capacity for shipment. The outage, which is the amount by which a tank falls short of being full, is typically two percent of tank volumetric capacity. Under movement and coupling, the tank lading is therefore free to slosh fore and aft longitudinally in the tank. During coupling impacts, fluid sloshing has the effect of dynamically reducing the lading mass coupling between the tank structure and the fluid. The fluids in the anvil and hammer cars will initially slosh toward the impacting ends of the cars with a time delay, which depends on the first natural mode of fluid sloshing. This extends the duration of the coupling force impulse, and reduces the peak coupling force necessary to bring the hammer and anvil cars to equal velocities, when compared to

a car with solid lading, as specified in AAR M901G-00. The dynamic pressures and total buff forces on the tank car heads during coupling impact are higher than the "end" forces on cars with solid ladings (e.g., hopper car end slope sheets, box car ends, bulkheads, etc.) because of the relatively lower fluid friction forces on the tank wall compared to the solid lading case in hoppers, etc.

In addition, as the fluid sloshes towards the tank head and begins to fill up the outage volume from the impact end of the tank towards the other end, there is a center of gravity (CG) increase of the fluid mass in each tank and absorption of coupling impact kinetic energy as storage of potential energy in the fluid.

Stub sill tank cars usually have curved ellipsoidal end heads, but for estimating purposes, a cylindrical tank shape will be assumed. The mathematical relationship between tank outage, tank radius, and center of fluid gravity (undisturbed) for cylindrical tanks is as follows:

Let R = tank inside radius
C = tank sector semi-angle
α = tank outage (ratio of segment volume to total tank volume)
x_0 = height of undisturbed fluid segment above tank center
y = height of undisturbed fluid CG above bottom of tank
y_s = height of undisturbed outage segment CG above bottom of tank
h = height of undisturbed fluid surface below top of tank
y/R = undisturbed fluid height of CG (non-dimensional ratio)
h/R = tank outage non-dimensional ratio
y_s/R = undisturbed fluid height of segment CG (non-dimensional ratio)

C is the solution to the transcendental equation

$$C - \cos C \sin C = \alpha\pi \tag{10}$$

$$x_0/R = 2 \sin 3C/(3(C - \cos C \sin C) \tag{11}$$

$$y/R = 1 - (x_0/R)(\alpha/(1 - \alpha)) \tag{12}$$

$$y_s/R = 1 + x_0/R \tag{13}$$

$$h/R = 1\text{-}\cos C \tag{14}$$

These results are plotted graphically in Figures 11 and 12.

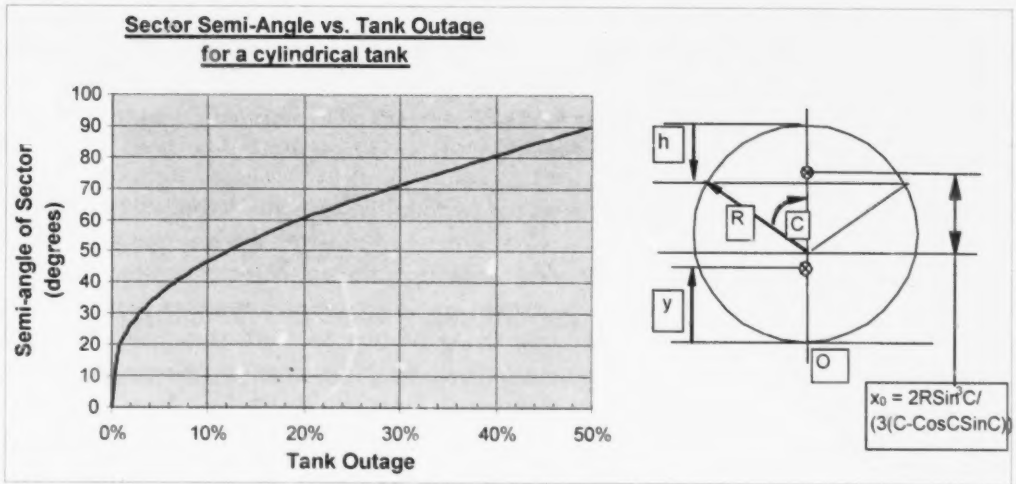


Figure 11. Tank Sector Semi-Angle vs. Tank Outage for Cylindrical Tanks

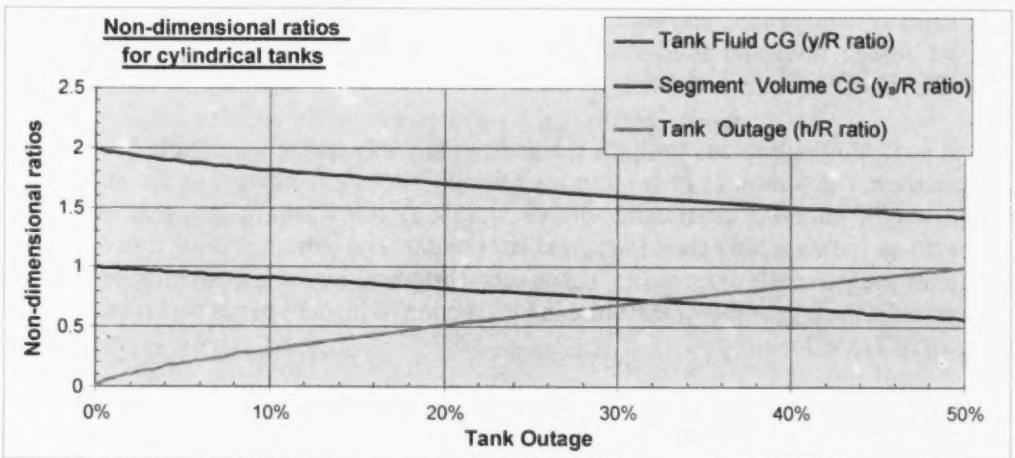


Figure 12. Non-Dimensional Ratio for Fluid CG, Segment CG, and Tank Outage for Cylindrical Tanks and Undisturbed Fluid as a Function of Tank Outage

For a cylindrical tank of 8 ft. 2 in. inside diameter (98 in.), the cross sectional area is 7,543 sq. in. Two percent outage is about 151 sq. in of area cross section per unit tank length. The tank outage (distance of fluid below top of tank) is 5 1/8 in. The center of gravity of the fluid load undisturbed is at 48 1/16 in. from tank bottom. If the fluid surged during a severe impact, and in the limiting case, filled the full cylindrical cross section from the impact end forward, the center of gravity of the fluid would rise to tank center (in the limiting case), or 49 in., an increase of 15/16 in. in this limiting case. The

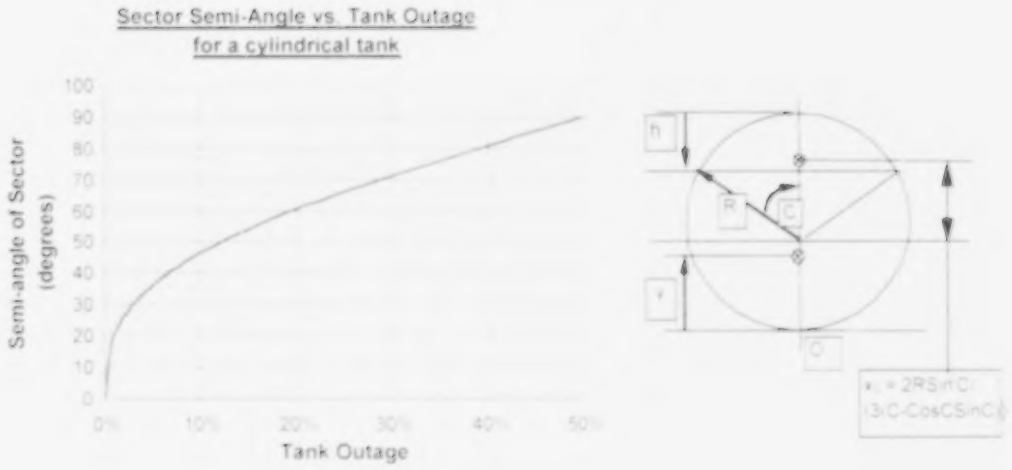


Figure 11. Tank Sector Semi-Angle vs. Tank Outage for Cylindrical Tanks

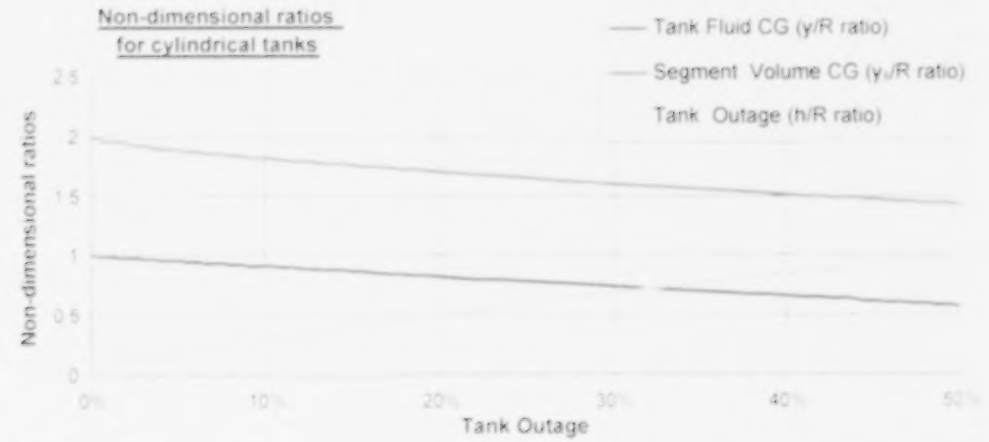


Figure 12. Non-Dimensional Ratio for Fluid CG, Segment CG, and Tank Outage for Cylindrical Tanks and Undisturbed Fluid as a Function of Tank Outage

For a cylindrical tank of 8 ft. 2 in. inside diameter (98 in.), the cross sectional area is 7,543 sq. in. Two percent outage is about 151 sq. in of area cross section per unit tank length. The tank outage (distance of fluid below top of tank) is 5 1/8 in. The center of gravity of the fluid load undisturbed is at 48 1/16 in. from tank bottom. If the fluid surged during a severe impact, and in the limiting case, filled the full cylindrical cross section from the impact end forward, the center of gravity of the fluid would rise to tank center (in the limiting case), or 49 in., an increase of 15/16 in. in this limiting case. The

potential energy change is of an order of 163,000 lb. x 15/(16 x12) = 12,734 ft.-lb., and is of the order of 1/4 of the draft gear energy absorption. This value will increase with increasing outage. In addition, fluid sloshing will increase the energy dissipation due to viscous losses in the lading, but these are dependent on the viscosity characteristics of the fluid lading.

4.3.4 Revenue Coupling Scenarios

The simple case of coupling one hammer car, with initial velocity, to one stationary anvil car, as specified in AAR M901G-00, is not typical of most of the revenue service yard switching couplings. In revenue flat yard or hump yard switching, the more frequently occurring type of coupling usually consists of one or more hammer cars, with the same initial velocity, coupling onto a standing string of two or more stationary anvil cars, which usually are free to roll. There are also some coupling situations where the standing cars may not be free to roll, such as in hump yard classification tracks, where the standing cars are restrained by an inert retarder at the end of the class track, or where cars are standing on a yard track without brakes bled off.

In hump yard operation, a double car cut is usually the maximum number of hammer cars released together in a target shot coupling from the crest of hump. Loaded tank cars are usually released as single cars. **However these are not generalized operating rules for all railway companies**, and each may have its own policy. As well, the cars may be mixed among fluid and solid load cars, and mixed with loads and empties of varying weights, in the hammer and anvil groups.

Most switching operations for both flat and hump yards attempt to couple loaded cars at target speeds of 4 mph or lower, but over 0 mph. A "short runner" (a car that does not reach target coupling destination before stopping) introduces a gap that reduces car capacity in the switching class track, and later requires an extra trimming move to couple. Empties are generally targeted at higher than 4 mph to increase switching productivity, because the draft gear provide cushioning protection to higher speeds for an empty car, as shown in Table 7.

To achieve a coupling within the above target coupling speed range, some manual judgment skill is needed in a flat yard, or measurement is needed in a hump yard, to know at what speed the car(s) should be released from the switching cut in the flat yard, or group retarder in the hump yard, in order that they actually reach and couple into the targeted anvil cars. In flat yard switching, the switching foreperson has no 'a priori' information on car weight (just whether they are loads or empties) or on rolling resistance or distance to couple. This person must rely on his or her skill as a switch person to judge car release velocities, and any error that produces too high a release velocity results in a potential "above 4 mph" coupling impact.

In hump yard switching, much more accurate information on car weight, rolling resistance, and distance to go is generally available for the class track target coupling shot; group retarder exit velocities are calculated by computer; and group retarders are computer controlled. However, unpredicted changes in rolling resistance, such as due to

wind gusts, changing snowfall conditions, etc., can lead to coupling impacts over 4 mph as well as "short runners", which do not couple.

Flat yard and hump yard coupling velocities are statistically distributed with a mean value of the order of 4 mph and a dispersion or standard deviation, and are skewed towards the 0 mph direction. The magnitude of the standard deviation will determine the values associated with overspeed coupling outliers and short runners. It will vary from yard to yard with employee skill, ambient conditions of weather and temperature, and hump yard control sophistication and maintenance. Typically, the standard deviation will be of the order of 0.5 to 1.5 mph.

4.3.5 Mathematical Relationships for Multi-car Couplings

The same general principle as was developed in Section 4.3 applies to multi-car couplings, i.e. system linear momentum before and after the coupling impact(s) is preserved. To get some insight into the mechanics of multi-car couplings, and to simplify the describing mathematics for purposes of understanding and developing trends, assume that all hammer and anvil cars have the same mass m = weight/gravity constant, and are all fitted with the same rated energy capacity draft gears. The momentum and kinetic energy equations for the impact are as follows:

Let N_h = number of hammer cars
N_a = number of anvil cars
m = mass of each car
V_i = initial velocity of the hammer car(s) just before impact
V_f = final velocity of hammer and anvil car(s) after impact

All in a set of consistent units.

Momentum before impact = momentum after impact

$$N_h m V_i = (N_a + N_h)\, m V_f \tag{15}$$

$$V_f = N_h V_i / (N_a + N_h) \tag{16}$$

The change in kinetic energy (ΔKE) after the impact becomes

$$\Delta KE = \{0.5m[(N_h V_i/(N_h + N_a)]^2 - 0.5 N_h m V_i^2\} \tag{17}$$

$$\Delta KE = -0.5\, m V_i^2 \{N_h [1 - N_h/(N_a + N_h)]\} \tag{18}$$

where the negative sign represents a loss of KE, and ΔKE = the energy absorbed by all draft gear, lading losses, suspensions, etc. in the coupled hammer/anvil string.

We see from (16) that the final velocity of the coupled hammer and anvil cars is reduced from the initial velocity by the factor $\mathbf{N_h/(N_a + N_h)}$. This **Final Velocity Factor** has been

plotted in Figure 13 for 1, 2, and 3 hammer cars versus 1 to 50 initially stationary anvil cars. The effect of increasing the number of hammer cars in the cut is to increase the velocity of the coupled string of hammer and anvil cars, after hammer car(s) impact at a given initial velocity. Increasing the number of anvil cars reduces the final velocity of the coupled string of cars after impact at a given initial velocity.

From equation (18), the kinetic energy that must be absorbed and dissipated during the multi-car coupling impact is equal to the factor $\mathbf{N_h[1 - N_h/(N_a + N_h)]}$ times the initial kinetic energy of an individual or single hammer car. This factor is called the **kinetic energy loss ratio**, and has been plotted in Figure 14 for 1, 2, and 3 hammer cars versus 1 to 50 initially stationary anvil cars.

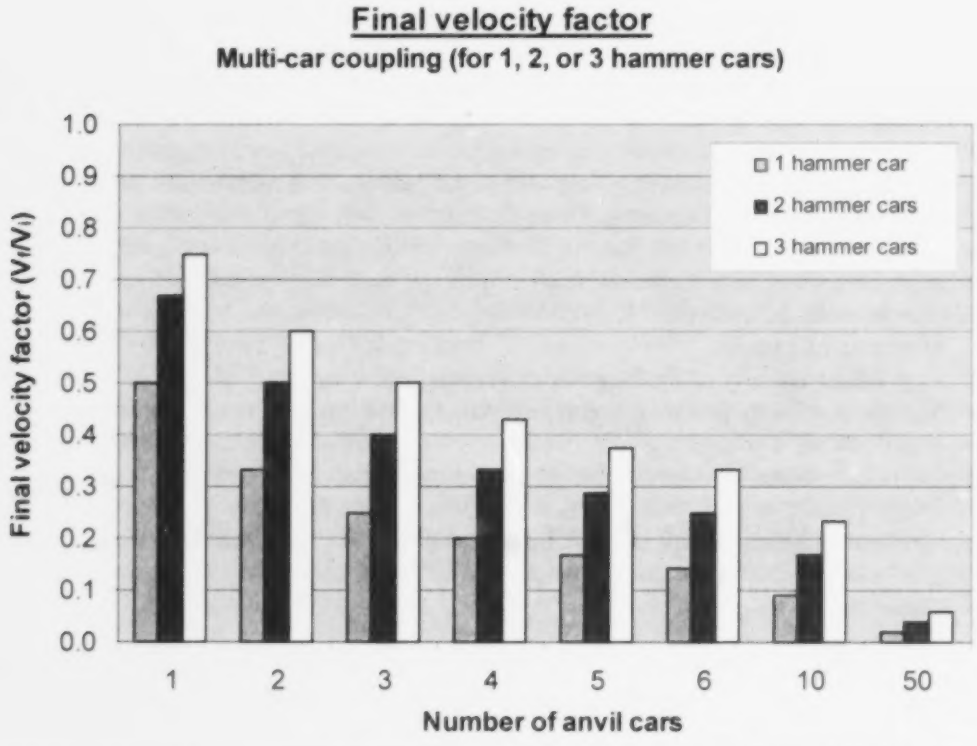


Figure 13. Final Velocity Factor after Multi-car Coupling Impact for 1, 2, and 3 Hammer Cars Coupling into from 1 to 50 Anvil Cars

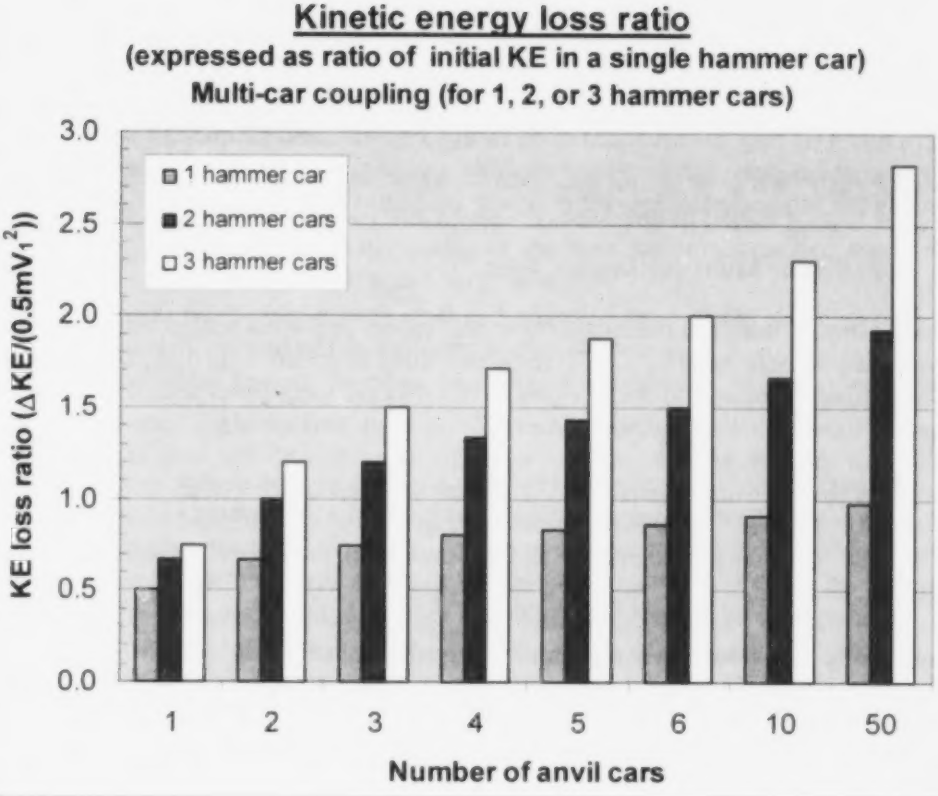


Figure 14. Kinetic Energy Loss Ratio for Multi-car Coupling Impact for 1, 2, and 3 Hammer Cars Coupling into from 1 to 50 Anvil Cars

The effect of increasing the number of hammer cars in the cut is to increase the system kinetic energy, which must be absorbed and dissipated by the draft gear, suspensions, lading, etc. in the coupled string of hammer and anvil cars, after hammer car(s) impact at a given initial velocity. Increasing the number of anvil cars significantly increases the kinetic energy to be absorbed and dissipated after impact at a given initial velocity. In Figure 14, three hammer cars impacting a single anvil car only increases the required KE loss ratio to 0.75, compared to 0.5 for a single hammer car. Increasing the number of anvil cars to 10 raises the required KE loss ratio to 2.3, compared to 0.9 for a single hammer car, because the final velocity of the coupled string, after impact, is reduced to 0.23 of the initial hammer car's velocity.

The most severe peak impact force situation occurs when a multi-hammer car group couples into a long stationary cut of anvil cars where, in the limit, all the initial KE must be absorbed and dissipated. The peak coupler forces will likely occur at the point of coupling, and the draft gears at the point of coupling will absorb something of the order of 3/4 of the total hammer car(s) kinetic energy when operating within and up to their rated energy capacity, but not solid.

In multi-car couplings, there are more draft gears available to absorb the increased loss requirement. The question that is analytically undetermined, by the kinetic energy method, is how to distribute the draft gear energy losses among the various draft gear coupled pairs, because of coupling free slack and the serial nature of the coupling process. Before the second to n^{th} draft gear pair in the coupled string react, the pair at the point of coupling may have reached rated energy capacity, and produced a solid condition and a maximum peak force. However, this analytical limitation may be resolved by reviewing the full-scale test data for multi-car couplings.

4.3.6 Full-scale Multi-car Impact Tests

Full-scale impact tests and multi-body dynamic model predicted results were carried out and reported in 1998 by NRC/CSTT for water filled tank cars with 1, 2, and 3 hammer cars impacting on from 1 to 5 anvil cars [13]. All cars were fitted with serviceable "as received" Cardwell-Westinghouse Mark 50 all-steel friction draft gears. The tests consisted of running a large series of coupling impacts with the tank cars filled with water to 98 percent volume capacity. With tank volumes about 11,585 imp. gal. and car tare weights of about 52,900 lb., the cars used in the impact tests had a laden gross rail load of only 169,000 lb., compared to their gross rail load at full weight capacity of 263,000 lb.

A multi-body non-linear dynamic model was developed using **ADAMS**, a software package for **A**utomatic **D**ynamic **A**nalysis of **M**echanical **S**ystems [14]. This included a representation for fluid sloshing and suspension vertical and pitching motions, and was calibrated against the full-scale impact test data at the GRL level of 169,000 lb. The model was then used to estimate the peak coupling forces for tank cars under the same multi-car impact configurations as the impact tests, with the cars loaded to 98 percent volume fill level, but with a higher density product like acid, to a gross rail load of 263,000 lb.

The report on the simulations concluded that the coupler pair at the initial point of impact generally produced the highest peak impact forces. Impacts with multiple hammer cars always produced higher peak impact forces for the same anvil conditions [14]. These observations are consistent with the above theory.

If the measured data, taken from the NRC/CSTT report for the cars at 169,000 lb. gross rail load, is used to calibrate the kinetic energy method previously discussed in Section 4.3.5, a relatively good correlation can be obtained for initial coupling velocities that cause the 500,000 lb. draft gear rated force level to be reached for multi-tank car impacts. It is noted that the kinetic energy method does not attempt to predict peak impact forces at coupling speeds above impact velocity ratings, but rather shows the coupling speeds at which the draft gear rated force level of 500,000 lb. will be reached. This implies that coupling above these speeds will cause peak impact forces to exceed 500,000 lb. draft gear buff forces.

The data comparison shown in Table 9 is plotted in Figure 15, and the correlation is relatively good (within 0.4 mph) for the last three of the four test multi-car configurations

3/2, 3/3, and 3/5 compared. The first case, 3/1, differs by 0.8 mph, but the method is useful as an estimator of trend for the heavier weight cars with different draft gear rated energy levels.

The kinetic energy model was matched to the impact test data by assuming:

- The Cardwell-Westinghouse Mark 50 draft gear in "as received" state still had a nominal 39,000 ft.-lb. rated energy capacity, as shown in Figure 7.
- The additional kinetic energy losses in the tank car structures and suspensions were 15 percent of the draft gear energy absorbed.
- The additional kinetic energy absorbed and dissipated in the sloshing tank fluid load was 100 percent of the draft gear energy absorbed.
- The draft gear pair at the point of coupling absorbs 3/4 of the system kinetic energy.

For the simplified case where all cars in a multi-car coupling are identical, the ΔKE loss equals the energy absorbed by all draft gears, lading losses, car suspensions, etc. in the coupled hammer/anvil string of cars. Applying the assumptions, bulleted above, to express the kinetic energy loss in terms of the assumed fraction lost at the hammer/anvil car and draft gear pair at the initial point of coupling, the ΔKE can be expressed as:

$$\Delta KE = 2 \times [1 + 0.15 + 1.00] \times \text{Gear rated energy capacity} = \Delta KE \text{ loss factor} \times 0.75\ (0.5 m V_i^2) \quad (19)$$

The initial velocity of the hammer cars, necessary to produce a 500,000 lb. peak draft gear force, at the coupling point for the different hammer/anvil combinations evaluated, is then estimated by equation (20):

$$V_i = \{2 \times [1 + 0.15 + 1.00] \times \text{Gear rated energy capacity}/[\Delta KE \text{ loss factor} \times 0.75 \times 0.5m]\}^{0.5} \quad (20)$$

where:

The factor 2 represents the presence of two draft gears at the point of coupling.

The term 0.15 represents the fraction of additional draft gear rated energy absorbed by one car's suspension at the point of coupling.

The term 1.00 represents the fraction of additional draft gear rated energy absorbed by one car's fluid sloshing, as determined in the correlation with NRC/CSTT test data described.

The factor 0.75 represents the assumed fraction of the anvil car(s) kinetic energy absorbed at the hammer/anvil car and draft gear pair at the initial point of coupling.

Table 9. Comparison of Measured Multi-tank Car Impact Velocities, which Produced a 500,000 lb. Peak Draft Gear Force, with Kinetic Energy Impact Model Calibrated to Match the Measured Data, all Tank Cars Loaded to 169,000 lb. GRL

Multi-car coupling test configuration	Measured impact velocity at 500,000 lb. draft gear force level	Predicted impact velocity at 500,000 lb. draft gear force level by kinetic energy method	NRC/CSTT report reference data		
			Case no.	Figure no.	Page no.
(# Hammer)/ (# Anvil)	mph	mph			
3/1	6.5	7.3	4	26	36
3/2	5.8	5.7	5	27	37
3/3	5.5	5.1	6	28	38
3/5	5.0	4.6	3	25	35
3/10	No data	4.1	-	-	-
3/50	No data	3.7	-	-	-

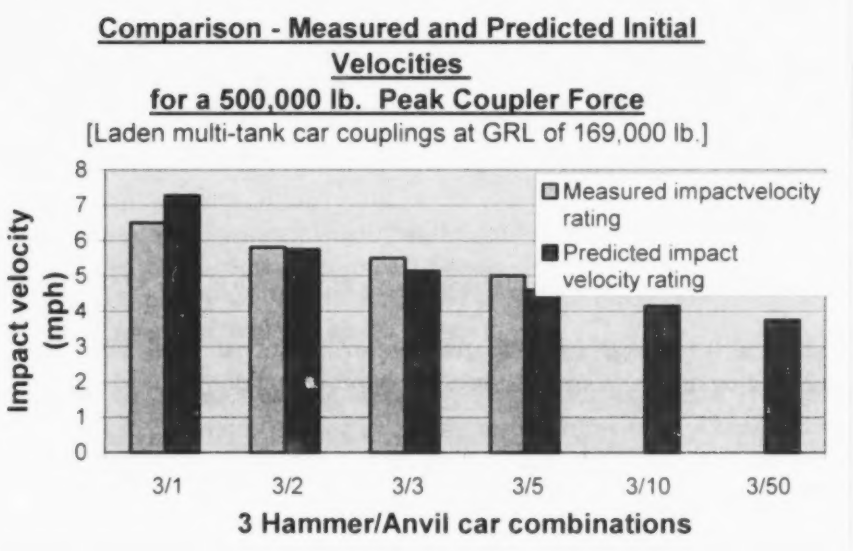


Figure 15. Comparison of Measured Multi-tank Car Impact Velocities, which Produced a 500,000 lb. Peak Draft Gear Force, with Kinetic Energy Impact Model Calibrated to Match the Measured Data, with All Tank Cars Loaded to 169,000 lb. GRL

4.3.7 Using the Calibrated KE Method to Extrapolate to 263,000 lb. Cars

An estimate of the maximum coupling velocities that the current AAR M901G-00 draft gear provides as a function of rated energy capacity, while limiting the peak draft gear buff force to 500,000 lb., in loaded multi-tank car coupling situations for cars with a 263,000 lb. gross rail load, is shown in Table 10. It is based on equation (20), using the calibrating assumptions from the NRC/CSTT impact tests for cars loaded to 263,000 lb. GRL.

An examination of the most severe kinetic energy case of a three-hammer car multi-anvil car coupling of laden 100-ton tank cars has been made. Table 10 shows that with draft gear at new rated energy capacity of 48,000 ft.-lb., coupling into a string of five anvil cars at an initial speed of 4.1 mph will produce peak impact forces of 500,000 lb., and this speed will drop to 3.3 mph for a very long string of 50 cars, as might be at rest in a hump yard or flat yard class track. As draft gear rated capacities deteriorate with service wear, these speeds are estimated to reduce to about 2.7 mph for a long string of 50 cars. These are worst-case scenarios, but they indicate that the current specification AAR M901G-00 draft gear cannot provide tank car structural protection limited to the 500,000 lb. level for typical yard coupling target speeds of 4 mph in the triple laden multi-hammer tank car case. The most critical situation for coupling into a tank car probably arises when it is at the head of a long string of anvil cars, and a cut of two or more loaded hammer cars that are not tank cars couples into it. The protective fluid sloshing effect would be missing from the anvil car group.

Table 10. Combinations of Multi-tank Car Coupling Speeds for 500,000 lb. Peak Coupler Forces for Different Draft Gear Rated Energy Capacities

Car nominal capacity (tons)	GRL (lb)	(Hammer cars) /(anvil cars)	3/1	3/2	3/3	3/5	3/10	3/50
100	263,000	KE Loss Factor	0.750	1.200	1.500	1.875	2.308	2.830
	DG Impact rated Energy capacity	(2.15 x DG Impact Energy rating	Impact Velocity Rating (estimated)[1]					
Notes	ft. lbs	ft. lbs	mph	mph	mph	mph	mph	mph
[2]	32,400	69,660	5.3	4.2	3.8	3.4	3.0	2.7
[3]	36,000	77,400	5.6	4.4	4.0	3.5	3.2	2.9
[7]	39,000	83,850	5.8	4.6	4.1	3.7	3.3	3.0
[4]	40,000	86,000	5.9	4.7	4.2	3.7	3.4	3.0
[5]	48,000	103,200	6.5	5.1	4.6	4.1	3.7	3.3
[6]	67,000	144,050	7.6	6.0	5.4	4.8	4.4	3.9

[1] Coupling at velocities above those tabulated will produce peak coupling forces greater than 500,000 lb.

Notes for energy ratings shown

[2] AAR M901B Minimum energy rating (non reconditioned state)
[3] AAR M901B Minimum energy rating (after reconditioning)
[4] AAR M901E Average energy rating (typical service worn 8 years)
[5] AAR M901E New energy rating (typical)
[6] New energy rating high capacity (friction/Hydraulic assist)
[7] New Cardwell-Westinghouse Mark 50 rated draft gear energy

4.3.8 Distribution of Coupling Impact Speeds

The distribution of coupling impact speeds tends to be asymmetric, like a Poisson distribution, with the longer tail on the low side of the mean. For the purpose of this work, the distribution is assumed to be normal with a mean of 4 mph, with a standard deviation from 0.5 to 1.5 mph. Table 11 shows the likely number of couplings that will exceed a given speed, assuming this normal distribution and various standard deviations from 0.5 to 1.5 mph, for every one million coupling events. The productivity of large hump yards ranges from about 500 to 3000 cars per day. Table 12 shows the number of days it will take to achieve one million coupling events, based on a typical range of hump yard productivity, and various values for the average number of hammer cars in a cut.

The following illustrates the meaning of the data presented in Tables 11 and 12. Table 12 shows that a hump yard with productivity of 1,500 cars a day and an average hammer car consist of 1.5 cars will take 1,000 days, or nearly three years, to achieve one million coupling events. If this yard has a standard deviation in coupling impact speed of 1 mph, then Table 11 shows that 40,059 cars will be expected to couple at a speed of 5.75 mph or more over that 1,000 day period. In other words, 40 couplings per day should be expected at a speed of 5.75 mph or more in this hump yard. About 18 percent of all freight cars are tank cars, so about 7 tank cars per day would be expected to be coupling at a speed of 5.75 mph or more. There would be fewer couplings expected at this speed for a lower standard deviation of coupling impact speed, and more for a higher standard deviation.

There are a total of about 58 major hump yard locations in North America. About half of these are in the northern part of the U.S. and in Canada, where "low" temperatures might be expected at least occasionally during each winter. The numbers used in the previous paragraph were chosen arbitrarily and strictly for illustrative purposes. Depending on the actual values of mean and standard deviation of coupling impact speed that the various yards achieve, it appears quite likely that significant and consistent numbers of couplings may be occurring at an impact speed well over 5 mph. A more accurate representation of the statistical distribution of coupling events would not be expected to change this conclusion dramatically.

4.4 Full-scale Draft Gear Tests at Low and Warm Temperatures

A series of draft gear full-scale impact tests were carried out by NRC/CSTT during April 2002, using two NRC/CSTT captive rail cars. The purpose was to measure the draft gear cushioning performance under low temperature and ambient temperature conditions to observe whether there was any change of draft gear performance. Energy rating capacity changes had been previously reported as shown in Figure 8, under low temperature conditions, during draft gear Tup testing in the laboratory by both Cardwell-Westinghouse and Miner. A Cardwell-Westinghouse Mark 50 draft gear with steel preload/return springs and friction clutches exhibited a 25 percent reduction of rated reaction force at low temperature in laboratory Tup tests, but draft gear frosting contamination on the friction clutch surfaces was felt by Cardwell-Westinghouse to have influenced this result.

Table 11. Number of Couplings per Million Couplings that Exceed a Given Impact Speed, for Various Standard Deviations in Coupling Impact Speed with a Mean of 4 mph

Impact Speed (mph)	Standard Deviation of Coupling Impact Speed				
	0.50 mph	0.75 mph	1.00 mph	1.25 mph	1.50 mph
4.00	500000	500000	500000	500000	500000
4.25	308538	369441	401294	420740	433816
4.50	158655	252492	308538	344578	369441
4.75	66807	158655	226627	274253	308538
5.00	22750	91211	158655	211855	252492
5.25	6210	47790	105650	158655	202328
5.50	1350	22750	66807	115070	158655
5.75	233	9815	40059	80757	121673
6.00	32	3830	22750	54799	91211
6.25	3	1350	12224	35930	66807
6.50	0	429	6210	22750	47790
6.75	0	123	2980	13903	33376
7.00	0	32	1350	8198	22750
7.25	0	7	577	4661	15130
7.50	0	2	233	2555	9815

Table 12. Number of Days for One Million Couplings, Based on Hump Yard Productivity and Average Number of Cars in a Hammer String

Yard Productivity (Cars/Day)	Average Number of Cars per Hammer String				
	1.00	1.25	1.50	1.75	2.00
500	2000	2500	3000	3500	4000
1000	1000	1250	1500	1750	2000
1500	667	833	1000	1167	1333
2000	500	625	750	875	1000
3000	333	417	500	583	667

For full-scale impact testing, the existing NRC/CSTT hammer car was filled with concrete to 234,000 lb. and the anvil car was filled with crushed stone to 241,000 lb. Both impacting ends were fitted with Cardwell-Westinghouse Mark 50 draft gear removed from serviceable NRC/CSTT cars for this test. A dynamometer drawbar was applied to the anvil car at the impacting end, and stroke transducers and thermocouples were applied to both draft gear. A long stroke string pot was applied between the anvil car and ground to estimate anvil car velocity during and after impact. A time/distance gate was used to measure the hammer car velocity, just before impact. Hammer car initial velocity was developed on the NRC/CSTT impact ramp.

The draft gear strokes were measured between the coupler follower plate and the sill, i.e. only the draft gear compression strokes were recorded during the impacts. These data were used to evaluate draft gear energy absorption (elastic stored plus dissipated) for the first impact compression stroke, which is the one producing the peak coupling force.

A special thermally insulated high density foam board thermal cooling housing was fabricated to enclose the sill/draft gear area of each car with the cars coupled together, to allow controlled pre-cooling with nitrogen gas to –58°F (anvil car) and –48.3°F (hammer car) over a 20 hour period prior to the impact tests. Figure 16 illustrates the cooling housing in place.

The thermal housings were then removed, and Figure 17 shows the surface frosting conditions. Low temperature impact testing commenced with the ambient temperature initially at +34.7°F and the draft gears at –21.1°F for the first impact. Ten low temperature impacts were made, covering the impact speed range of 2.9 mph to 4.32 mph, over a period of about 2 1/2 hours, during which the draft gear warmed to about +21.2°F and the ambient temperature increased to +49.6°F. Considerable frosting contamination developed on the cold surfaces of the sills, draft gears, and couplers once the housings were removed. The ambient humidity conditions at air temperatures in the range of +34.7°F to +49.6°F were a sufficient source of moisture for the frosting to occur.

Figure 18 shows the underside of the sill with LVDT stroke transducer and string pot applied to capture draft gear buff stroke. Figure 19 shows the hammer and anvil cars coupled, with frosting on couplers and sills seen.

Similarly, these housings were also used to allow heating of the draft gears to +79.5°F (anvil car) and +78.8°F (hammer car). Twelve warm temperature impacts were carried out, covering the impact speed range of 2.83 mph to 5.11 mph, over a period of about four hours, with ambient temperature initially starting at +63.1°F and draft gears at +70.7°F (hammer car) and +65.7°F (anvil car). The draft gears had cooled to approximately +66.2°F and ambient had risen to +68°F by the end of these impact tests.

Figure 20 shows the peak impact forces recorded for each series. The plot shows that the draft gear rating force of 500,000 lbf was reached at 3.3 mph for the low temperature test series, and at 4.7 mph for the warm test series for these car weights, which are marginally higher (6 to 10 percent) than the AAR M901E-00 or M901G-00 specification

requirement of 220,000 lb. There was a significant loss of rated energy capacity for the cold draft gear case.

It is suspected that the frosting contamination on the draft gear affected the surface friction of the draft gear's wedge faces, leaving a thin film of ice on them. This severely reduced energy dissipation and draft gear reaction force at rated stroke, after the first impact while cold. These tests confirm Cardwell-Westinghouse low temperature laboratory Tup tests, reported in Section 4.2.3.

It is evident that if the draft gear friction surfaces become contaminated with ice, the performance of the draft gear drops significantly below specification. The issue, then, is to determine whether the friction surfaces can become contaminated in such a manner as to impair performance significantly under some operating conditions. For example, snow crystals do pack into the draft sill pocket due to air turbulence under a train when it is in motion at speed and picks up snow from the roadbed, draft gear may frost when a tank car is loaded or unloaded inside a warm building then moved outside in the winter, or rain may penetrate the draft gear and freeze overnight. There may be a variety of other natural mechanisms that could contaminate draft gear friction surfaces.

Cardwell-Westinghouse low temperature laboratory Tup tests, reported in Section 4.2.3, found that elastomeric draft gear had a significant increase in peak force at low temperature. These draft gear may also be a source of forces that may damage a stub sill under low temperature conditions. This is an area for further investigation, because in a tank car's case, the purpose of the draft gear is to protect the car structure, not the lading.

In summary, impact tests were conducted at a low temperature with the draft gear temperature in the range –21 to +21°F, and in warm conditions with the draft gear temperature in the range 65°F to 70°F. The draft gear reached its rated force capacity of 500,000 lb. at 3.3 mph in the low temperature tests, and at 4.7 mph for the warm test series. The capacity of this friction draft gear was significantly reduced when its friction surfaces were contaminated by frost. Comparable results have been found in laboratory tests.

Figure 16. Foam Board Thermal Housing Applied to Coupler/Sill Area of Both Cars during Cooling of Draft Gears with Expanded Liquid Nitrogen Gas

Figure 17. Interior of Cold Housing after Cool Down of Couplers, Draft Gears, and Sill Area, Cold Housing is Being Disassembled to Start Testing

Figure 18. Underside of Sill Showing the LVDT and String Pot Transducers to Capture Draft Gear Buff Stroke

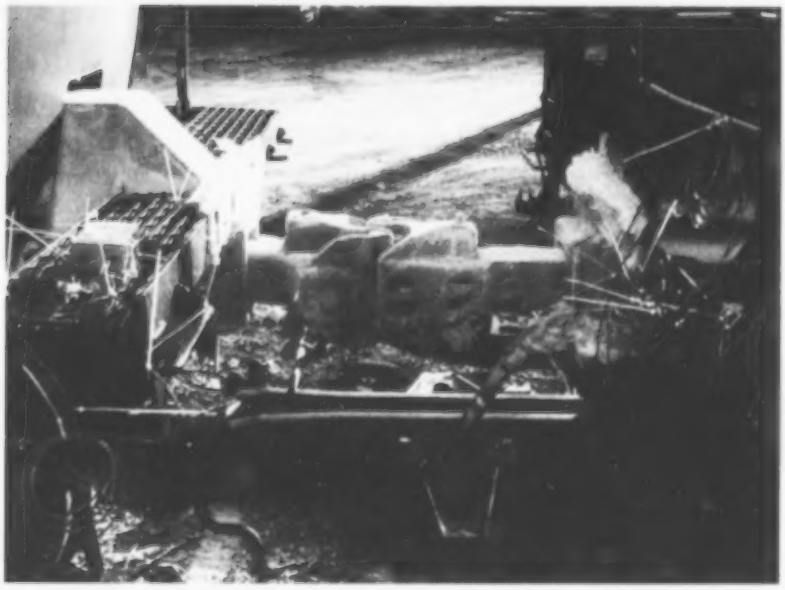


Figure 19. Hammer and Anvil Cars Coupled with Frosting Seen on Couplers and Sills

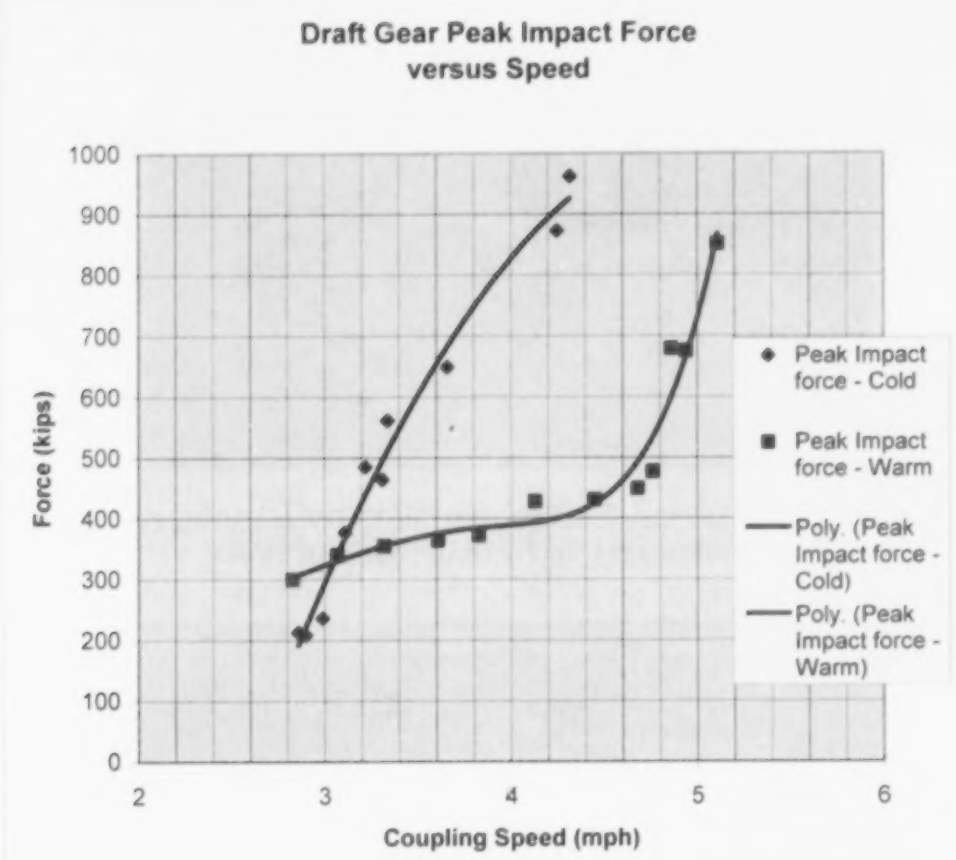


Figure 20. Draft Gear Peak Impact Force vs. Coupling Speed for Cold and Warm Conditions

5.0 TANK CAR STEEL MATERIAL PROPERTIES

The fracture toughness of a material provides a measure of the resistance of a structure, containing a crack-like defect, to failure. For railroad tank car applications, the primary variables influencing toughness include material strength, operating temperature, loading rate and local geometric effects (e.g. stress concentrations, thickness of structure and presence of welds). Each of these variables affects the observed toughness in a complex and synergistic manner.

One of the primary goals of the literature review was to determine the role that these variables play on the fracture toughness of materials relevant to the tank car impact problem. Admittedly, this is a difficult task considering the complexity of the overall fracture event and the different variables involved. To further complicate matters, there is not simply one parameter used to quantify fracture toughness. A variety of methods are typically used and understanding what the literature contains requires fully understanding the toughness measures employed.

To achieve these objectives, this discussion is divided up into a number of areas. First, the different parameters used to measure toughness are described. The test standards and methods are then described, followed by a summary of the literature.

5.1 Property Definitions

The fact that the inherent toughness of a structural material increases with increasing temperature is fairly well known. Quantifying the increase for a given material can be done using a variety of fracture toughness tests and specimen geometries. What is less widely recognized, however, is that fracture toughness can decrease significantly with increasing loading rate. Furthermore, testing specimen geometries thinner than that required for plane-strain behavior in the material can result in toughness values that are increased. Decoupling the influence of all of these variables is clearly a difficult task and depends to some extent on the fracture toughness parameter employed.

When one talks about the generic "toughness" of a material, it is critically important to ensure that the meaning of toughness is fully understood. Toughness can refer to a Charpy V-notch energy or, alternatively, an elastic-plastic fracture parameter used to describe the onset of slow, stable crack advance (as well as a myriad of other toughness parameters in between these two). The different parameters that can be used to define toughness are described herein, based on extensive testing experience as well as the descriptions contained within references [15, 16].

5.1.1 Toughness Measures Using Methods prior to the Development of Fracture Mechanics

When focused on ferrous materials, the term "toughness" is often academically misused to refer to results obtained from a Charpy V-notch (CVN) test. Prior to the development of fracture mechanics, the CVN impact test was the one most widely used to determine toughness for a given structural material. During this type of test a v-notched, three-point

bend bar is struck by a pendulum with the resulting fracture parameter equal to the absorbed energy to fracture the specimen. Hence, one normally quotes values in foot-pounds and the toughness parameter is really a CVN energy value. For example, the AAR M-1002 specification [17] requires that AAR TC128 steel for low temperature service be normalized to meet a CVN energy of 15 ft.-lb. at –50°F. CVN tests are typically performed for a given material at different temperatures resulting in an energy-toughness curve.

The CVN test is perhaps the most inexpensive method that can effectively be used to determine the basic "toughness" of a material. However, using an energy value from a CVN test in design typically requires converting it to one of the more traditional fracture mechanics toughness measures. Although a considerable amount of work has been performed developing the relationships that relate the two, these methodologies are empirically based and depend on whether the CVN test result is from the upper shelf (higher energy, higher temperature), lower shelf (lower energy, lower temperature) or transition region between the two portions of the energy-temperature curve [18]. For the purposes of this discussion, suffice it to say that methods to relate the different parameters do exist (although they typically require empirical calibration to some extent).

Yet another criticism of the CVN test is related to what is measured during the test. There is no differentiation between crack initiation and propagation energy in the specimen. Furthermore, the other issue that is worth mentioning with a CVN test is that the specimen is not fatigue precracked with a sharp notch prior to testing, but rather the specimen geometry is blunt notched (0.010 in. root radius). Clearly the applicability of a blunt notch to a sharp crack tip can be problematic; nevertheless, the specimen is inexpensive, the test is quick and the method has been used for many years to correlate absorbed fracture energy to service performance.

Several other test methods, somewhat related to the CVN test but addressing the notch acuity, size effect and absence-of-weld issues inherent in this test, are used to quantify the impact toughness or impact toughness-temperature relationship. These methods include the dynamic tear (DT) test, drop-weight tear (DWT) test and nil-ductility transition (NDT) temperature test. The dynamic tear test utilizes a three-point bend specimen larger than the CVN test: 1.6 in. wide by 7 in. long with a notch length 0.5 in. long (typical thickness of 0.625 in.). This specimen has a sharper notch (0.001 in. root radius) than the CVN specimen. However the results from the DT test are similar to that from a CVN test: absorbed energy units.

The specimen used for the drop weight tear test is similar to the oversize, three point bend specimen geometry used in the DT test. However, it is slightly larger: 3 in. wide with a total overall length of 12 in. and a thickness equal to the full plate thickness of the product evaluated. In this case, the notch is short (0.2 in.) with a sharp notch root radius of 0.001 in. However, the DWT test is focused on quantifying the fracture appearance in terms of percent shear area. Hence, no measurements are made of the energy required to fracture. Typically this test is performed on identically sized specimens over a range of temperatures to illustrate how shear area changes with temperature.

The nil-ductility transition temperature test is similar to the DWT test in that the results are used to determine the temperature at which fracture does not occur in a brittle (100 percent shear) manner. Above the NDT temperature, the material has sufficient ductility to bend as opposed to fracture. Both long (12 in.) and short (4 in.) specimens are used with a variety of widths in three-point bending. In the center of the specimen opposite the middle loading point is a brittle weld bead in which a saw cut (relatively blunt notch) is made to localize the fracture. Fewer than ten specimens are typically used to determine the NDT temperature of a material.

The four methods presented in this section are essentially performed under impact-type loading (either pendulum or a dropping weight). Two of the test methods (CVN and DT) quantify absorbed energy values required to result in specimen fracture. The other two methods yield different measures typically tied to determining specifically how material behavior varies with temperature. In the case of the DWT test, a percent shear area is used with an unwelded sample to indicate how fracture appearance varies with temperature. This is contrasted to the NDT test in which a blunt notch in a weld bead is impacted to determine the transition between gross specimen bending and fracture.

5.1.2 Toughness Measures Derived from Fracture Mechanics Methods

What is known today as the science of fracture mechanics was driven primarily by the Liberty Ship failures during World War II [19]. Driven by a necessity to create a large number of cargo ships quickly during the war, 2700 liberty ships were built utilizing an all-welded hull, as opposed to the riveted construction of traditional ship designs. Four hundred of these ships sustained fractures, of which 90 were considered serious (10 ships completely fractured in two pieces) [19].

An enormous amount of research and development related to fracture control and design methodology has ensued over the past 50 years. Fracture mechanics focuses on what occurs at the crack tip and what parameters dictate behavior, especially instability, in this region. In general, fracture mechanics can be divided into two regimes:

- *Linear-Elastic Fracture Mechanics (LEFM)* – In this case, the stress field around a sharp crack in a structural member can be characterized in terms of a single parameter called a stress intensity factor K. LEFM is valid and applies only so long as nonlinear material deformation is confined to a small region surrounding the crack tip.

- *Elastic-Plastic Fracture Mechanics (EPFM)* – This case applies to higher energy fracture when small-scale yielding assumptions are violated and higher levels of gross plasticity are evident. Two similar parameters can be used to describe behavior at the crack tip: the J contour integral and crack tip opening displacement (CTOD) measurement.

Of these two regimes, the more highly developed of the two is LEFM due primarily to the fact that EPFM is a more recent development augmenting situations when LEFM principles are violated. In fact, considerable effort has been made extending linear-elastic principles into the elastic-plastic regime since design methodologies using LEFM are more robust and developed than those based on EPFM principles. Both approaches are critical for tank car stub sill materials since it is not uncommon for cracks in the medium-strength steels utilized in these structures to develop large plastic zones.

One of the underlying principles of fracture mechanics is that unstable fracture occurs when the stress intensity factor reaches a critical value [18]. The following toughness parameters are commonly used to describe instability for linear-elastic conditions:

- K_{Ic} – the critical stress intensity factor for quasi-static loading and plane-strain (thick member) conditions of maximum constraint. As long as plane-strain conditions are met, this parameter is independent of thickness.

- K_{Ia} – the critical stress intensity factor for a *running* crack given plane-strain conditions of maximum constraint.

- $K_{Ic}(t)$ or K_{Id} – the critical stress intensity factor for dynamic (rapid or impact) loading conditions given plane-strain conditions of maximum constraint. $K_{Ic}(t)$ is used where t indicates the time to failure whereas K_{Id} is typically used for impact loading. $K_{Ic}(t)$ can be either slower or more rapid than the impact test depending on which rate regime is desired.

- K_c, K_a, $K_c(t)$, K_d – the critical stress intensity factor (as described above) but where the specimen thickness is insufficient to meet the plane-strain requirements. These toughness parameters tend to be highly dependent on specimen thickness (and often cracked specimen geometry), hence the degree of plane-stress exhibited in the cracked configuration.

Stress intensity factor units are ksi√in. To complicate matters further, all of the fracture toughness parameters described above are dependent on the temperature and loading rate for the steels relevant to the tank car industry. Furthermore, the presence of welds can also affect overall toughness level.

In general, the plane-strain toughness measures described above apply to brittle fracture (e.g. lower energy) conditions. As energy increases, so too does the capacity for slow, stable crack advance and large plastic zone size development prior to unstable fracture. When stable crack advance occurs, the crack gradually grows as loading increases until, presumably, either unstable fracture occurs or the crack grows completely through the uncracked ligament. In this case, the primary result from a fracture test is what is called a resistance curve (R-curve). A resistance curve relates the applied stress intensity factor K (assuming LEFM conditions prevail and including a plastic zone size correction to calculate K based on crack length and the applied load) throughout the test to the crack length a or, alternatively, crack length extension Δa. For a K_c test, the point of instability

is the K value from the R-curve at the maximum load. Sometimes K_c is also designated K_R if something unusual occurs or if different instability conditions are applied during the fracture test.

The R-curve concept is also applied when performing an elastic-plastic fracture toughness test to determine J_{Ic}. However, in this case the J contour integral is substituted for K as described in the previous paragraph. The J_{Ic} toughness is effectively the plane-strain fracture toughness under quasi-static loading conditions given that conditions of elastic-plastic fracture mechanics apply. Large amounts of slow, stable cracking are typically observed in this test. The R-curve methodology, using J versus a or Δa in this EPFM case, differs somewhat in that the instability condition that defines J_{Ic} corresponds to a specific, small amount of crack extension (nominally 0.008 in.). For conditions where specimen thickness is insufficient for plane-strain conditions to dominate, fracture can be defined by a J_c toughness parameter. The units on a J integral toughness are ksi-in.

It is useful to briefly review how LEFM and EPFM parameters apply relative to the toughness-temperature relationship nominally observed for steel [18]. The K_{Ic} type of evaluation nominally applies to lower shelf or the lower end of the transition behavior. An elastic R-curve analysis (K_c) is typically restricted to the lower end of the transition behavior. The J_c or J_{Ic} toughness parameters typically apply for the transition and upper shelf region. These regions of applicability for the different toughness parameters make it difficult to know *a priori* which type of test is necessary. Since each test is quite different in the approach utilized, including different specimen sizes and geometries, it is extraordinarily difficult to efficiently perform the experiments and insure that "valid" fracture toughnesses are generated. Consequently, it is common to observe one test methodology applied to the full range of behavior with "invalid" test results at one extreme. Hence, care must be taken to interpret fracture toughness results that are available in the literature.

One toughness parameter that applies to the complete lower, transition and upper shelf toughness-temperature relationship is the crack tip opening displacement (CTOD). However, the CTOD approach is more commonly used in Europe than in North America. Nevertheless, the CTOD parameter (typically labeled δ) is based on the determination of a critical strain at fracture from the load-displacement behavior recorded during the fracture test. As should be expected with a parameter that applies to the full range of fracture behavior, there are a number of different CTOD parameters that can be derived from a fracture test. These include the following:

- δ_c – CTOD value at unstable cleavage fracture with no evidence of slow crack growth (ductile tearing),
- δ_u – CTOD value at unstable cleavage fracture after slow crack growth,
- δ_m – CTOD value at the first time maximum load is reached,

- δ_{ic} – CTOD value at the first point of brittle crack extension (pop-in), which is followed by a subsequent increase in load, and

- δ_{id} – CTOD value at the onset of stable crack extension (special instrumentation required).

As expected, the CTOD parameter has units of length (inches) associated with it.

5.2 Test Methods and Standards

The previous discussion highlighted the numerous fracture test methods that are available to assess toughness. The overall complexity of the fracture process is reflected in the large number of parameters used to quantify behavior. Luckily, most of these fracture toughness parameters have well-defined tests associated with them. A listing of the parameters and test standards is contained in Table 13 as extracted from the latest ASTM specifications [20]. Also contained in Ref. [20] is a standard "E1823-Terminology Relating to Fatigue and Fracture Testing" that establishes a common framework to ensure consistent terminology between the different standards.

It is worthwhile to briefly note some of the differences between the standards listed in Table 13. There are two types of standards listed: a standard test method and a standard practice. These two different types of tests are defined by ASTM as follows:

- Standard Test Method – a definitive procedure for the identification, measurement and evaluation of one or more qualities, characteristics or properties of a material, product, system or service that produces a test result.

- Standard Practice – a definitive procedure for performing one or more specific operations or functions that does not produce a test result.

Of the classifications, the standard practice is a less stringent type of material evaluation directed more at a methodology than producing standard test results. Standard practices are typically employed as situations where significant latitude is required in the laboratory during conduct and analysis of the test results.

All of the fracture mechanics based toughness parameters discussed previously use through-cracked specimen geometries. Unfortunately the situation sometimes relevant to tank car structure is a crack that is not fully through the thickness of the steel. The last entry in Table 13 refers to a surface crack test method that, although germane to the tank car structural issues, has to our knowledge not yet been applied.

Table 13. Description of the Relevant ASTM Standard Associated with Each Test Method

Description	Abbreviation or Parameter	ASTM Standard	Title of ASTM Test Standard	Miscellaneous Comments
Charpy V-notch	CVN	E23	Standard Test Methods for Notched Bar Impact Testing of Metallic Materials	
Dynamic Tear	DT	E604	Standard Test Method for Dynamic Tear Testing of Metallic Materials	
Drop Weight Tear	DWT	E436	Standard Test Method for Drop-Weight Tear Tests of Ferritic Steels	
Nil Ductility Transition Temperature	NDT	E208	Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels	
Plane-strain Fracture Toughness	K_{Ic}	E399	Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials	
Crack Arrest Toughness	K_{Ia} (or K_a)	E1221	Standard Test Method for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, of Ferritic Steels	
Dynamic Fracture Toughness	$K_{Ic}(t)$ (K_{Id})	Annex A7 (E399)	Special Requirements for Rapid-Load Plane-Strain Fracture Toughness $K_{Ic}(t)$ Testing	No codification yet for K_{Id} (US Steel and Lehigh Univ. have procedures)
Plane-stress Fracture Toughness	K_c (K R-curve)	E561	Standard Practice for R-Curve Determination	
Plane-strain J R-curve	J_{Ic}	E813	Standard Test Method for J_{Ic} , A Measure of Fracture Toughness	Discontinued in 1997
Plane-strain or –stress J R-curve	J_{Ic} or J_c (as well as others)	E1820	Standard Test Method for Measurement of Fracture Toughness	Latest version – termed the combined method since it relates to K, J and CTOD measurement
Crack Tip Opening Displacement (CTOD)	$\delta_{c,\ u,\ m,\ ic\ or\ id}$	E1290	Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement	Also British Standard 5762
Surface Crack Toughness	K_{max}	E740	Standard Practice for Fracture Testing with Surface-Crack Tension Specimens	This standard is currently undergoing a significant re-working and revision

5.3 Literature Summary

Performing a material property search required first identifying the relevant materials. Based upon the SwRI DTA program [21], the following materials were identified:

- A36 and A7
- A516 (grade 60 and 70)
- A572, A441
- A515, A612
- TC128

As another source, a listing of the allowable materials from the Code of Federal Regulations 49 CFR Parts 100 to 185 identifies A285 material (as well as several of the materials listed above). In addition to an electronic search of the scientific literature, searches of government reports (FRA and TC), AAR and industrial reports were also performed. In addition to the listing of material properties contained in Ref. [21], 20 additional key references worthy of note were identified. These references [18, 22 to 40] are sorted in terms of material and specific property identified in Table 14.

Several observations are apparent from Table 14. First, no data were available for A283 (admittedly, an older material not commonly used in modern design). Second, there is a plethora of Charpy impact data available for the materials. Finally, the NDT, DWT and DT data were confined to three additional sources [25 to 27].

One reference that proved particularly useful and contains a wealth of toughness data is the Eiber and Olson report [26]. This 1975 report, entitled "Material Study on Steels Used in Current and Former Tank Car Construction and from Cars Involved in Accidents" contains an enormous amount of data, albeit mainly impact data with no fracture mechanics related toughness.

Perhaps the most notable observation from Table 14 is that only a few materials have fracture mechanics toughnesses available (TC128B in the normalized condition, A515, A572 and A36). This is significant because the fracture mechanics-based methods provide data most suitably used for design.

While it might be desirable to tabulate and present the actual property values from the references listed in Table 14, this would likely not be a valuable source of property data for a number of reasons. First, each reference considers materials that come from different sources: some from real structure, some from special mill creations, some with and without alloying elements, some with welds, and some simply bought on the open market. Although the alloy designations are a useful discriminator, a considerable range of strength levels would be apparent for a number of the materials that would likely obfuscate any application of the property values. Furthermore, many of quantities are not well summarized by single values. Consider by way of example a CVN toughness value. Depending on the temperature, the toughness can range from lower to upper shelf, a span

of probably 60 ft.-lb. for TC128B. Hence, the CVN toughness is not well tailored to single-point definition suitable for a simple tabulated presentation. In fact most of the properties in Table 14 are not well suited to single value quantification. A tabulated summary with actual property values of the information in Table 14 would overly simplify material differences and potentially result in misleading summary judgments regarding materials.

Table 14. Summary of Tank Car Steel Material Property Data References

Material Property	Tank and Head Materials							Stub Sill and Head Brace Matls		
	TC128B (as rec.)	TC128B (norm.)	A516 Gr. 70	A515 Gr. 70	A212	A285C[1]	M115	A572 Gr. 50	A36	A283 Gr. 50
CVN	[26] [27]* [31] [33]	[26] [27]* [28] [36] [37] [39]	[26]	[26] [34]	[26] [30]	[26] [29] [32] [35]	[26]	[18]	[18] [24]	
NDT	[26]	[26]	[26]	[26]	[26]	[26]	[26]			
DWT	[26]	[26]	[26]	[26]	[26]	[26]	[26]			
DT	[25] [26] [27]	[25] [26] [27]	[25] [26]	[25] [26]	[25] [26]	[26]	[26]			
Kc or Jc or CTOD		[36] [39]		[22] [23]				[18]	[18] [24]	
Ka or Kd		[38] [39] [40]+		[23]				[18]	[18]	
K R-curve								[18]		

Key: * = base metal, HAZ and weld metal data
+ = HAZ

[1] This material is also used in construction of the stub sill and head brace.

6.0 DESIGN AND ANALYSIS PRACTICES

6.1 Current Approaches

In addition to the literature review for this project, current design practices that may be used to take into account the possibility of a low temperature impact on a tank car were investigated. To accomplish this, SwRI conducted an informal telephone survey of a number of engineers employed by US tank car builders and owners. In every case, each engineer that was contacted requested that his name and his company name be kept anonymous for proprietary reasons. Therefore, the discussion that follows does not specifically reference any tank car builder or owner; responses have been distilled such that they present a broad overview of current industry practice.

It appears that the sole method used by the tank car industry to address low temperature issues is via the material specifications; i.e., the AAR's specifications for tank cars, M-1002 [17], requires that AAR TC-128 steel for low temperature service be normalized to meet a CVN energy of 15 ft.-lb. at –50°F for new construction of pressurized tank cars. This specification applies to base metal and does not address the energy absorption capability of weldments, although one manufacturer reported performing CVN tests on tank car steel weldments. It was pointed out, however, that more and more customers who will be using tank cars in low temperature service are now requesting verification of CVN values for the tank shell and head materials.

It was noted in a number of discussions that sill materials are not subject to the same CVN material specifications as the tank shell and head materials. In some cases, builders or owners are specifying their own Charpy requirements on sill materials.

In general, no one had in place structural design/analysis practices that *specifically* address tank car impacts at low temperatures. Not surprisingly, the prevailing practice is to use a static "squeeze" load of one million pounds to design the cars as specified in M-1002 [17], keeping stresses below yield. A design is subsequently verified for impact loading using a "dynamic squeeze" test in which a tank car is subjected to successive impacts at 2 mph increments up to 1.25 million pounds. These dynamic squeeze impact tests are generally performed without regard to the environmental temperature; i.e., specific efforts to perform such a test at a low temperature have generally not been made.

Therefore, while a number of the tank car builders and owners use finite element analysis (FEA) to analyze the static strength of tank cars, we found virtually no one who performs numerical dynamic calculations to analyze the behavior of tank cars under yard impact (collision) events. In fact, one respondent indicated that it is more economical to just perform an impact test (instead of investing the time and manpower it would take to perform a dynamic FEA of an impact event, and validate the results).

6.2 Fracture Analysis Procedures

Given that the current approach to fracture-resistant design appears to only consider the Charpy energy of tank car steels, it is certainly not surprising to find that the industry is generally *not* applying fracture mechanics analysis procedures to address the integrity of railroad tank cars at low temperatures combined with impact loadings. Ironically, a substantial number of Safety Project reports documenting the use of fracture mechanics techniques to address these types of problems were published by W. S. Pellini in the late 1970s and early 1980s. (An extensive bibliography of Pellini's reports is listed in Appendix C.) At the time of their publication, these procedures could probably have been considered state-of-the-art. Nevertheless, in our discussions with industry personnel, no one was found to be routinely using Pellini's analysis methods today as a fracture-safe design tool. In fact, it is indeed discouraging to see that any current knowledge or understanding of this large body of work is merely anecdotal in nature and that this technology has not been passed down to the current generation of tank car engineers.

A brief description of Pellini's fracture analysis methods, sometimes referred to as the "slide-graph" procedure, is provided for reference in Appendix D. For additional details, the reader is referred to the numerous Pellini references listed in Appendix C and D.

Recent work performed for the RPI-AAR Safety Project by Sims Professional Engineers [8] has used Pellini's method to help analyze the fracture behavior of tank car steels in accidents (see the discussion in Section 3.1.3). However, this work and the earlier work by Pellini [9] appear to use a somewhat arbitrary criterion to distinguish between ductile and brittle failures. Accidents having punctures or fractures larger than 18 in. were labeled brittle; conversely, punctures or fractures smaller than 18 in. were considered to have been ductile because of the absence of extensive crack propagation [8, 9]. SwRI was unable to discern a quantitative basis for this "rule of thumb" from the literature that was reviewed. It should be recognized that rapid ductile fracture is not an impossibility and that large-scale ductile fracture is also possible [41], albeit at a slower rate than a propagating brittle fracture. Conversely, a brittle fracture could initiate and possibly arrest as it encounters a stiffer, reinforced region, prior to attaining a length of 18 in. Hence, this 18 in. "rule of thumb" that has been used in the past to distinguish between a ductile and a brittle fracture is quite arbitrary and should be verified.

6.3 Impact Loading

The tank car structure is cushioned from high coupling impact forces by the draft gear, located in the stub sill and connected to the coupler. When the kinetic energy of an impact event exceeds the capacity of the two draft gears, buff forces will rise rapidly due to car inertial mass and longitudinal structural stiffness. To properly assess the susceptibility of tank cars to an impact induced failure, these *external* dynamic loads must be determined and then converted to *local* strains and stresses (along with their associated loading rates) at critical structural details such as locations of frequently occurring cracks [42] and stress "hot spots" determined by static analyses and tests [21].

While there have been numerous past efforts to characterize and/or model tank car impact forces, e.g. Refs. [13, 14, 43-45], including ongoing efforts by the Safety Project [46], the challenge has been, and continues to be, the use of these dynamic forces in a structural integrity assessment that accounts for:

- Specific local geometry details
- Local loading rates (strain and/or stress as a function of time)
- Material properties as a function of temperature and loading rate

An effort to integrate many of these input variables in an assessment of tank car failures was included in Ref. [8] by Anderson and elsewhere [47]. These analyses employed the use of a failure assessment diagram (FAD) approach in conjunction with Monte Carlo probabilistic simulations to predict lading loss as a result of ductile and brittle fractures. While Refs. [8 and 47] used an idealized loading distribution that could be debated, this simplified loading model served as an expedient representation of the dynamic load environment for the purposes of accomplishing that work.

While the current tank car loads data [43] are believed to be representative of over-the-road (OTR) load events, the presence and/or accuracy of yard impact events in these data have been questioned. In addition, reliable information is not currently available regarding the phasing (coupling) of the vertical coupler force (VCF) and longitudinal coupler force (LCF) loads; since the OTR data were rainflow counted, sequence data are also not available. Nevertheless, based on an examination of a limited amount of LCF force-time data, SwRI estimates that loading rates during an over-speed impact may be on the order of 10^3 ksi$\sqrt{\text{in}}$/sec. This is considered an intermediate loading rate, slower than what occurs in Charpy tests, but rapid enough such that dynamic effects must be addressed.

Two industry/government groups, the Tank Car Operating Environment Task Force (TCOE-TF) and the Stub Sill Working Group (SSWG) are currently involved in developing and implementing technology to better understand the operating environment of tank cars. This work is being performed by the AAR's Transportation Technology Center, Inc. (TTCI) and is jointly funded by RPI member companies, the AAR, the FRA and TC. Although this effort is still under way, early progress was documented in Ref. [46].

A key, and most likely the highest priority, result to obtain from these current load recording efforts is a detailed characterization of the actual yard impact load environment, including determination of the phasing of the longitudinal and vertical load components, loading rates, and the range of load magnitudes and their corresponding frequencies of occurrence. These results will provide an indication of how to revise the damage tolerance analysis load spectra [21] to properly include impact events as well as provide data to generate statistical distributions of these extreme events for use in a probabilistic risk analysis of failure during an impact event.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the literature and technology reviews performed to date by SwRI and NRC/CSTT concerning the effects of low temperature impacts on railroad tank cars, a number of conclusions and recommendations are provided below, grouped by general technical areas.

7.1 Operational

Small numbers of coupling incidents that result in tank car failure and product spillage appear to be directly traceable back to a particular severe event. It is possible that damage initiated by a moderately severe coupling event may not result in product spillage until long after the event.

The most critical situation for a tank car probably arises when it is at the head of a long string of anvil cars, and a cut of two or more loaded hammer cars, which are not tank cars, couples into it.

The most common overspeed coupling events that occur in high-volume flat yard and hump yard switching, with a coupling speed standard deviation greater than 1 mph about a 4 mph mean, are significantly more severe than the 5 mph event specified for rating draft gear. The types of draft gear most widely used in tank cars may reach their rated capacity well below 5 mph, despite the attenuation in coupling force provided by the fluid load sloshing effect. Flat yards or hump yards that aim to couple at an average speed of 4 mph are likely to have significant numbers of couplings in excess of 5 mph.

Recommendation No. 1:

> The RPI-AAR Accident Database provides a wealth of historical accident information. These data could be used to develop frequency plots (such as Figures 2 and 3) for use in probabilistic risk assessments. However, it is probably more appropriate to use site-specific climatological (temperature) data instead of the distribution plotted in Figure 3. Development of a representative distribution of yard impact speeds for each yard (conceivably by speed recording and/or video) would enable site-specific risk analyses to be performed.

7.2 Tank Car Impacts and Draft Gear Behavior

Tank cars built prior to 1974 with a nominal buff capacity of 800,000 lb. have a much higher risk of damage as a consequence of a severe coupling impact than cars built since that date with a buff capacity of 1,250,000 lb. The older cars still comprise about 16.2 percent of the total fleet of tank cars.

It is difficult to evaluate the low temperature performance of draft gear other than by conducting full-scale impact tests at the required low temperature.

The capacity of a friction draft gear is significantly reduced when its friction surfaces are contaminated by frost. It is possible to imagine circumstances that could contaminate the friction surfaces, but the extent to which these occur in revenue service, and their effects, are unknown. The resistance of an elastomeric friction draft gear increases significantly at low temperature. There are no performance requirements for draft gear at low temperature. The capacity of friction draft gear is also somewhat reduced by wear and there are performance requirements for rating reconditioned draft gear.

Recommendation No. 2:

> Low and warm temperature comparison impact testing of cars fitted with elastomeric draft gear typical of the types (M901G-00) used by the car builders should be carried out to determine the loss of impact velocity rating that may occur during low temperature coupling impacts.

Recommendation No. 3:

> A more quantitative evaluation of the tank car sloshing effect and its incrementally increased impact peak force protection during coupling impacts should be undertaken to confirm the rather large magnitude of the effect seen in the multi-tank car coupling impacts.

Recommendation No. 4:

> For the CTC/DOT 111A tank cars built prior to 1974 (approximately 43,000 cars in the North American fleet), higher capacity draft gear should be evaluated, as an option to be retrofitted in the 24 5/8 in. stub sill pocket, to provide these "weaker" cars with higher impact velocity rating and more protection against overspeed coupling impacts, which can lead to tank cracking and product leakage. The number of stub sill tank failures related to all coupling events is remarkably low, considering the millions of tank car miles operated by the North American tank car fleet since the introduction of the stub sill tank car. These early tank cars range from 29 to 40 years old, and may be retired from service within the next decade or so. Nevertheless, many of the products carried in the 111A cars are hazardous, so that transportation safety rather than cost benefit may be the driving principle.

7.3 Fracture Safe Design

From the large number of AAR reports authored by W.S. Pellini, it is apparent that 20 to 25 years ago there was an initiative made to implement a fracture mechanics-based technology to address the combination of low temperature and dynamic loadings that can potentially have a deleterious influence on the structural integrity of railroad tank cars. Since it appears that the sole method of addressing these issues today is by specifying a Charpy energy requirement for tank car steels, the tank car industry has not kept pace with the advances in structural integrity technology that have been made in other

industries that rely on welded steel structures. See, for example, the fitness-for- service practices that are recommended by the American Petroleum Institute [48] and similar procedures used elsewhere [49].

While the CVN impact fracture toughness test is widely used as a toughness indicator for structural steels, its development predates the development of fracture mechanics and as such does not evaluate the influence of notches versus cracks, nor does it account for the size (thickness) effect. Moreover, it strictly applies to loading rate conditions that may or may not be representative of typical tank car impact scenarios. Although it is a valuable screening method, these limitations directly hamper applying CVN results in a fracture mechanics or damage tolerance-based fracture control framework, thus precluding the determination of critical crack sizes and the specification of usage-based inspection intervals.

Recommendation No. 5:

> The "fracture-safe design" technology and guidelines put forward 20 years ago by Pellini should be modernized to take advantage of advances in technology made in the last two decades. In particular, this would involve using updated fracture mechanics models (e.g., those contained in NASGRO® [50]), possibly adopting a failure assessment diagram (FAD) approach as recommended by API RP-579 [48], and certainly putting the entire package in a user-friendly, computerized format.

7.4 Fracture Toughness

Much attention has been given over the years to improving the toughness characteristics of steels used in tank car construction and there are numerous references in the tank car literature documenting how new materials with increased toughness will affect accidents. For instance, Ref. [26] makes the following statement:

> *"For TC128-B material, no significant transition temperature improvement can be achieved by changing to other pearlitic type steels. It was concluded that the TC128-B steel is an optimum product for the service and that changes are not justified on the basis of the fracture properties."*

Examining another reference, for example [8], the following statement is made:

> *"Thus the use of normalized steel (and even a "hypothetical" steel which would totally eliminate brittle fractures) would provide a minimal reduction in lading losses."*

The problem with both of these statements is the basis used for making the argument. Datasets available for the materials are few. Never are more than two or three replicate samples used. And finally, but most importantly, the service environment typical of tank

car operation has not been applied in the materials test laboratory when generating these data.

In service, the environmental issues can be fairly severe both with regard to temperature and loading environment. Superimposing the two of these effects (temperature and loading rate) on a moderate strength steel with typical lot-to-lot scatter as well as the variability that occurs when the structure is welded can lead to an enormous scatter in the overall material property variability. It is believed that these variabilities are a significant contributor to the brittle low temperature failures that have occurred in service.

Another way to look at this effect is to consider that, for the most part, the steels used have sufficient toughness. There is no question about this since brittle failures are still a relatively rare event. Given this, the question is how then do we end up with a brittle failure? First, high-speed impacts do occur and cold temperatures are common, especially in Canada. Both of these effects tend to create a situation where you effectively operate in the lower tail of the toughness distribution. When the circumstances are such that this occurs, brittle failures are possible.

Understanding the loading rate issue is believed to be a key to understanding what is happening in the structure. Recent proprietary testing performed by McKeighan at SwRI on A572 structural steel used in a large structure clearly illustrated (a) a large amount of fracture toughness variability and (b) an increase in this variability as loading rate increased. Fracture toughness values for the material under high rate loading not unlike that subjected to tank cars yielded toughnesses on the order of 30-40 ksi$\sqrt{in}$ (this is a fairly low level). The toughness decrease noted between quasi-static and high rate loading was approximately a factor of 2-3X. Additional similar data is provided in reference [23] for A515-70 steel. However, in this case 12 replicate tests were performed at –7°C. Fracture toughness was observed to vary by over a factor of 8X in this baseline condition. When tested at high rate, the toughness decrease that was observed was between a factor of 3-4X. The implication is clear. With an 8X toughness variation in the baseline condition and a significant knockdown for high rate loading conditions, had a sufficient number of specimens been tested there would have clearly been a very low toughness result (presumably much lower than the 30-40 ksi$\sqrt{in}$).

Therefore, it is believed that the occurrence of failures under low temperature impact conditions is a statistical variability issue that is exacerbated and not fully understood due to limited testing budgets and few replicate specimens in past work. If operating conditions were farther away from the lower shelf temperature, this would be less of an issue, but in the region where toughness is changing as a function of temperature, a significant amount of variability in properties can be observed. Combining this variability with scatter due to lot-to-lot material variations, the presence of welds, and uncertain loading rates may result in higher risk due to larger overall "system" variability that is not particularly well understood.

Recommendation No. 6:

The absence of virtually any high rate fracture toughness data at relevant loading rates and temperatures makes it difficult to interpret behavior under impact or high rate conditions (typical for many failures). A modest effort investigating high rate fracture toughness should be undertaken. To aid in interpretation for the tank car structure, high rate fracture toughness tests yielding effectively a K_{Ic} value will be undertaken. Variables that could be exercised in the test matrix would include material (TC128B in normalized and non-normalized form, as well as a couple of other typical sill materials), service temperature, presence of welds, loading rate, material lot and repeatability, thickness and material vintage. This type of testing would go a long way towards understanding tank car steel behavior at loading rates relevant to overspeed impact accidents and at low service temperatures.

7.5 Probabilistic Risk Analyses

As evidenced by the preceding discussions, understanding the low temperature impact problem is dependent on a number of key parameters, many of which have inherent uncertainty (e.g., material properties such as yield strength, toughness, transition temperature, etc.) or statistical uncertainty (e.g., impact load magnitudes and rates, operating temperatures, existing flaw or crack sizes, etc.). In addition, the assumptions contained in the analysis methods may result in modeling errors, i.e. the use of simplified models to represent complex behavior. Assessments of the influences of such random variables on structural integrity and reliability require probabilistic approaches; however, probabilistic methods require considerably more data than mean or upper bound values used in traditional deterministic analyses. An example of such an approach, used to investigate the sensitivity of tank car stub sill cracking to a number of random variable inputs, can be found in Ref. [51].

Recommendation No. 7

Much of the information documented in this report can be used to formulate a probabilistic approach that will enable the risk of low temperature impact failures to be quantified. In parallel with recommendations Nos. 1 through 6, a probabilistic risk analysis approach should be developed to account for the interactions of the many random variables that contribute to the response of the tank car under these conditions. Moreover, a probabilistic analysis will identify the most significant parameters governing the structural performance of a tank car under low temperature impact conditions. The results obtained would provide information and guidance to implement a comprehensive validation program supported by detailed analytical modeling. In addition, the results of probabilistic risk analyses would provide a quantitative basis for developing operational guidelines to reduce the risk of low temperature impact accidents.

REFERENCES

[1] "Ensuring Railroad Tank Car Safety," Transportation Research Board, Special Report 243, Washington D.C., 1994.

[2] Railinc, Data summary based on UMLER Master File as of 16 March 2003.

[3] "North America's Hump Yards," *Trains Magazine*, June and July 2002.

[4] National Water and Climate Centre, U.S. Department of Agriculture, http://www.wcc.nrcs.usda.gov/water/climate/

[5] Canadian Climate Normals 1961-1990, Canadian Meteorological Centre, Environment Canada, http://www.cmc.ec.gc.ca/climate/normals/eprovndx.htm

[6] Treichel, T.T., "RPI-AAR Database of Tank Car Mechanical and Damaged Data," RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR, Washington, D.C., June 2001.

[7] Hazel, M.E., Jr., "Tank Car Accident Data Analysis," Report No. DOT/FRA/ORD-91-05 (DOT-VNTSC-FRA-91-3), Volpe National Transportation Systems Center, Cambridge, MA, June 1991.

[8] Hughes, J.P., Heuer, C.F. and Anderson, T.L., "Fracture Behavior of Tank Car Steels in Accidents from 1981 through 1994," Sims Professional Engineers, AAR Report No. R-924 (Report No. RA-03-6-62), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR, Washington, D.C., December 1998.

[9] Phillips, E.A. and Pellini, W.S., "Phase 03 Report on Behavior of Pressure Tank Car Steels in Accidents," AAR Report No. R-553 (Report No. RA-03-6-48), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, IL, June 1983.

[10] "Tank Car Failure with the Release and Ignition of Propane, Selkirk, New York, March 6, 1996," NTSB Report No. HZB-98-02, National Transportation Safety Board, Washington, D.C., April 20, 1998.

[11] "Couplers and Freight Car Draft Components, Specification M901, Manual of Standards and Recommended Practices," Section B, Association of American Railroads, Washington, D.C., 1997.

[12] "Design, Fabrication, and Construction of Freight Cards, Specification M1001, Manual of Standards and Recommended Practices," Section C, Part II, Volume 1, Association of American Railroads, Washington, D.C., 1997.

[13] Tong, X. and Dong, R. "Multi Tank Car Impact Tests and Analysis - Report I: Yard Impact Testing," TC Report TP13192E, NRC Technical Report CSTT-RYV-TR-031, National Research Council Canada, Ottawa, ON, March 1998.

[14] Xu, J.Z. and Dong, R. "Multi Tank Car Impact Tests and Analysis - Report 3: ADAMS Model Simulations of Tank Car Impact," TC Report TP13359E, NRC Technical Report CSTT-RYV-TR-033, National Research Council Canada, Ottawa, ON, October 1998.

[15] *Mechanical Testing and Evaluation*, ASM Handbook Volume 8, H. Kuhn and D. Medlin, Eds., ASM International, Materials Park, OH, 2000.

[16] McKeighan, P.C., "Testing of Metallic Materials," Chapter 19 from the *Handbook of Materials Selection*, M. Kutz, Ed., J. Wiley & Sons, New York, NY, pp. 519-542, 2002.

[17] *Specifications for Tank Cars*, M-1002, Association of American Railroads Manual of Standards and Recommended Practices, Section C – Part III, Washington, D.C., 2000.

[18] Barsom, J.M. and Rolfe, S.T., *Fracture and Fatigue Control in Structures – Applications of Fracture Mechanics*, Second Edition, Prentice-Hall, New York, NY, 1987.

[19] Anderson, T.L., *Fracture Mechanics – Fundamentals and Applications*, First Edition, CRC Press, Inc., Boca Raton, FL, 1991.

[20] *2001 Annual Book of ASTM Standards*, Section 3: Metals Test Methods and Analytical Procedures, vol. 3.01, ASTM, West Conshohocken, PA, 2001.

[21] Cardinal, J.W., McKeighan, P.C. and Hudak, S.J., "Damage Tolerance Analysis of Tank Car Stub Sill Cracking," Final Report, SwRI Project No. 06-6965, Southwest Research Institute, San Antonio, TX, November 1998.

[22] Gao, X., Dodds, R.H., Jr., Tregoning, R.L., Joyce, J.A. and Link, R.E., "A Weibull Stress Model to Predict Cleavage Fracture in Plates Containing Surface Cracks," *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 22, pp. 481-493, 1999.

[23] Gao, X., Dodds, R.H., Jr., Tregoning, R.L. and Joyce, J.A., "Weibull Stress Model for Cleavage Fracture under High-Rate Loading," *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 24, pp. 551-564, 2001.

[24] Sorem, W.A., Dodds, R.H., Jr. and Rolfe, S.T., "Effects of Crack Depth on Elastic-Plastic Toughness," *International Journal of Fracture*, Vol. 47, pp.105-126, 1991.

[25] Pellini, W.S., Eiber, R.J. and Olson, L.L., "Phase 03 Report On Fracture Properties of Tank Car Steels – Characterization and Analysis," Report No. RA-03-4-32 (AAR R-192), RPI-AAR Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, IL, August 1975.

[26] Eiber, R.J. and Olson, L.L., "Final Phase 03 Report, Material Study on Steels Used in Current and Former Tank Car Construction and from Cars Involved in Accidents," Report No. RA-03-5-33 (AAR R-193), RPI-AAR Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, IL, August 1975.

[27] Phillips, E.A., Eiber, R.J., Coughlin, S.A., Heideman, P.B. and Fec, M.C., "Evaluation of New Steels for Tank Cars," Report No. RA-03-7-53 (AAR R-643), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, IL, April 1987.

[28] Phillips, E.A., "Evaluation of New Steels for Tank Cars, Phase II," Report No. RA-03-9-59 (AAR R-773), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, IL, May 1991.

[29] Rocheleau, D.C., "Rail Tank Car Failure," Report No. LP 56/94, Transportation Safety Board of Canada, Engineering Branch Report, May 9, 1994.

[30] Rocheleau, D.C., "Tank Car Wheel Gouge," Report No. LP 41/95, Transportation Safety Board of Canada, Engineering Branch Report, May 17, 1995.

[31] Rocheleau, D.C., "Tank Car Head Plate Failure," Report No. LP 21/96, Transportation Safety Board of Canada, Engineering Branch Report, June 27, 1996.

[32] Rocheleau, D.C., "Tank Car Failure," Report No. LP 51/96, Transportation Safety Board of Canada, Engineering Branch Report, August 9, 1996.

[33] Mathieu, M.J., "Examination and Analysis of Fracture to Centre Bottom of Derailed Tank Car," Report No. LP 57/96, Transportation Safety Board of Canada, Engineering Branch Report, June 25, 1996.

[34] Rocheleau, D.C., "Tank Car Plate Failure," Report No. LP 50/97, Transportation Safety Board of Canada, Engineering Branch Report, June 11, 1997.

[35] Rocheleau, D.C., "Sulphuric Tank Car Mid-Span Fracture," Report No. LP 186/97, Transportation Safety Board of Canada, Engineering Branch Report, February 24, 1998.

[36] Hicho, George E. and Smith, John H., "Mechanical Properties and Fracture Toughness of AAR TC128 Grade B Steel and A Micro-Alloyed, Control-Rolled

Steel, A 8XX Grade B, From -80°F to +73°F," NIST Report No. 90-4289, (No. 19), National Institute of Standards and Technology, Gaithersburg, MD, April 1990.

[37] Hicho, George E. and Smith, John H., "Determination of the NDT Temperature and Charpy V-Notch Impact Properties of AAR TC128 Grade B Steel and A 8XX Grade B Steel," NIST Report No. 4300, (No. 20), National Institute of Standards and Technology, Gaithersburg, MD, April 1990.

[38] Hicho, George E., "Crack Arrest Fracture Toughness Measurements of Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel, and Micro-Alloyed, Control-Rolled, and Inclusion Shape Controlled A 8XX Grade B Steel," NIST Report No. 4501, (No. 21), National Institute of Standards and Technology, Gaithersburg, MD, February 1991.

[39] Hicho, George E. and Harne, Donald E., "Mechanical Properties and Fracture Toughness of AAR TC128 Grade B Steel in the Normalized, and Normalized and Stress Relieved Conditions," NIST Report No. 4660 (No. 24), National Institute of Standards and Technology, Gaithersburg, MD, September 1991.

[40] Hicho, George E. and Harne, Donald E., "Weld and Heat Affected Zone Crack Arrest Fracture Toughness of AAR TC128 Grade B Steel," NIST Report No. 4767 (No. 25), National Institute of Standards and Technology, Gaithersburg, MD, February 1992

[41] Kanninen, M.F. and Popelar, C.H., *Advanced Fracture Mechanics*, Oxford University Press, New York, NY, 1985.

[42] "Stub Sill Inspection Database, SS-2," Association of American Railroads - Railway Progress Institute, Washington, D.C., 1992-1999.

[43] Cogburn, L.T., "Stub Sill Tank Car Research Project: Results of a 15,000-Mile Over-the-Road Test," Technical Report FRA\ORD\95-11, Association of American Railroads, Pueblo, CO, September 1995.

[44] Dong, R. and Militaru, D., "Dynamic Structural Characterization of Stub-Sill Tank Cars Utilizing ADAMS and ANSYS Models. Report I - The ADAMS System Dynamic Model - Its Validation and Application to the Characterization of Impact Forces," NRC Technical Report No. CSTT-VC-TR-010, National Research Council Canada, Ottawa, ON, March 1997.

[45] Prabhakaran, A., Sharma, V. and Pena, J., "Effects of Coupler Height Mismatch on Tank Car Stub Sills," *Rail Transportation 2000*, RTD-Vol. 19, S.K. Punwani, Ed., ASME Rail Transportation Division, pp. 49-54.

[46] Koch, K.D., Riddell, W.T., Treichel, T.T. and Barkan, C.P.L., "Structural Response and Coupler Forces During Tank Car Impacts," *Proceedings of the 43rd*

Mechanical Working and Steel Processing Conference, The Iron and Steel Society, Vol. XXXIX, October 2001, pp. 837-848.

[47] Anderson, T.L., "Probabilistic Fracture Mechanics Analysis of Lading Loss in Railroad Tank Cars," *Proceedings of the 43rd Mechanical Working and Steel Processing Conference*, The Iron and Steel Society, Vol. XXXIX, October 2001, pp. 883-894.

[48] "Recommended Practice for Fitness-For-Service," API RP-579, American Petroleum Institute, Washington, D.C., January 2000.

[49] "Guide on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures," BS 7910, British Standards Institution, London, England, December 1999.

[50] "NASGRO® Fracture Mechanics and Fatigue Crack Growth Analysis Software," Version 4.02, NASA-JSC and SwRI, San Antonio, TX, September 2002.

[51] Cardinal, J.W. and Enright, M.P., "Tank Car Stub Sill Damage Tolerance Analysis (DTA) Sensitivity Studies," *Proceedings of the 43rd Mechanical Working and Steel Processing Conference*, The Iron and Steel Society, Vol. XXXIX, October 2001, pp. 895-906.

APPENDIX A

Subset of RPI-AAR Tank Car Accident Database Containing Yard Impacts at Less than 50°F

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
AAR0013923	01/27/1994	PQ	2	-22	-99	1969	285	C	0.4370	0.4370	105.12	285	C	0.5000	105.12	20000	2	1
0530002A85	01/21/1985	PA	2	-22	5	1964	212	B	0.6280	0.6280	103.00	212	B	0.6560	103.00	18372	1	1
9801	01/25/1996	MN	2	-19	2	1994	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	21000	2	0
AAR0006207	01/31/1980	MB	2	-18	5	1973	285	C	0.4370	0.4370	113.12	285	C	0.4370	113.12	22800	2	0
AAR0007786	01/23/1982	MB	2	-18	10	1962	285	C	0.3750	0.5000	92.00	285	C	0.5000	92.00	12181	1	0
AAR0005752	12/27/1984	AB	2	-15	-99	1977	-99	-99	0.5620	0.5620	-99.00	-99	-99	0.5620	-99.00	33669	2	0
AAR0007892	02/28/1982	ON	2	-14	4	1965	-99	-99	0.4370	0.4370	-99.00	-99	-99	0.4370	-99.00	17000	2	0
AAR0011065	12/21/1983	AB	2	-13	7	1969	285	C	0.4370	0.4370	105.12	285	C	0.5000	105.12	20000	2	1
AAR0011638	12/29/1988	SK	2	-10	4	-99	-99	-99	-99.0000	-99.0000	-99.00	-99	-99	-99.0000	-99.00	-99	2	0
AAR0013858	12/10/1995	AB	2	-10	8	1982	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	24267	2	0
AAR0007709	12/15/1981	AB	2	-7	99	1970	515	7	0.4370	0.4370	102.00	515	7	0.4370	102.00	21000	2	0
AAR0005983	02/06/1984	MB	2	-5	0	1974	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	14000	2	0
AAR0012971	01/18/1992	BC	2	-1	-99	1969	128	B	0.6250	0.6250	118.05	128	B	0.6870	118.05	34059	2	0
AAR0013820	02/25/1995	AB	2	0	-99	1966	128	B	0.6530	0.6530	112.00	128	B	0.6530	112.00	33500	2	0
AWN1039B	11/19/1981	OH	2	0	0	1965	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	14000	2	0
AAR0001843	01/21/1970	WV	2	0	4	1967	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33500	2	1
019407010	01/19/1994	KY	2	0	5	1972	516	7	0.4480	0.4480	112.00	516	7	0.4480	112.00	23501	2	0
AAR0013660	11/18/1994	AB	2	0	8	1988	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	29947	2	0
AAR0013660	11/18/1994	AB	2	0	8	1982	128	B	0.4370	0.4370	110.25	515	7	0.4690	110.25	30000	2	0
AAR0008199	11/24/1985	ON	2	0	15	1973	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	23000	2	0
AAR0001843	01/21/1970	WV	2	0	1	1967	515	-99	0.7500	0.7500	85.00	115	-99	0.7500	85.00	11000	1	0
0940004B82	02/11/1982	OH	2	0	19	1961	285	C	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	10129	1	1
AAR0009666	12/11/1975	DE	2	1	99	1973	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	20700	2	1
AGR116	02/07/1978	MI	2	2	0	1948	212	A	-99.0000	-99.0000	78.00	212	A	-99.0000	78.00	8000	1	0
780228	02/08/1978	MN	2	3	0	1976	128	B	0.5620	0.5620	119.00	128	B	0.5620	119.00	34000	2	0
780228	02/08/1978	MN	2	3	0	1976	128	B	0.5620	0.5620	119.00	128	B	0.5620	119.00	34000	2	0
AVA0038	01/11/1982	VA	2	3	0	1970	212	B	0.8120	0.8120	102.37	515	7	0.8120	102.37	30000	2	0
AF8481	01/10/1997	IL	2	3	2	1989	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	23601	2	0
AAR0013310	02/15/1993	PQ	2	3	4	1966	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33500	2	0
AAR0007244	02/12/1985	SK	2	3	3	1950	285	-99	-99.0000	-99.0000	-99.00	-99	-99	-99.0000	-99.00	16000	1	0
0920001A82	01/12/1982	IN	2	4	-99	1975	516	7	0.4370	0.4370	87.50	516	7	0.4370	78.00	11000	2	0
EA30	12/17/1983	IL	2	4	3	1982	515	7	0.4370	0.4370	96.37	515	7	0.4370	94.50	14000	2	0
0382OR201	03/12/1982	OR	2	4	4	1972	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
AAK0065	01/17/1982	OH	2	5	0	1971	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	17000	2	0
0199CE002B	01/02/1999	WY	2	5	0	1970	128	B	0.6250	0.6250	119.00	128	B	0.6870	119.00	33695	2	0
AAR0014417	02/25/1997	CO	2	5	2	1970	128	B	0.6250	0.6250	117.88	128	B	0.6870	117.88	33885	2	0
0199CE002A	01/02/1999	WY	2	5	15	1969	128	B	0.4370	0.4370	115.12	515	7	0.4370	115.12	31300	2	1
391431	03/04/1978	MO	2	6	3	1953	285	C	0.7030	-97.0000	-97.00	-97	-97	0.7030	-97.00	11000	1	0
AAR0008029	02/12/1983	ON	2	7	-99	1974	285	C	0.4370	0.4370	113.12	285	C	0.4370	113.12	22800	2	0
PA0029	01/05/1991	WA	2	8	0	1968	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33715	2	0
A84010201	01/03/1984	ME	2	8	2	1968	128	B	0.7780	-97.0000	-97.00	-97	-97	0.8120	-97.00	17000	2	0
AAR0014635	06/13/1998	Tx	2	8	4	1992	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	25498	2	0
494708	12/25/1997	MS	2	8	5	1980	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	23618	2	0
AAR0005036	03/10/1974	SK	2	8	-99	1961	212	B	0.9060	0.9060	88.19	212	B	0.9060	88.19	17000	1	0
AAR0006365	06/24/1985	BC	2	9	3	1975	516	7	0.4370	0.4370	94.50	516	7	0.4370	94.50	13580	2	1
B87016	01/25/1987	MA	2	10	-99	1967	515	7	0.4370	0.4370	105.12	515	7	0.5000	105.12	15000	2	0
B87016	01/25/1987	MA	2	10	-99	1968	515	7	0.4370	0.4370	105.12	515	7	0.5000	105.12	15000	2	0
AAR0011987	12/14/1989	KS	2	10	-99	1974	515	7	0.4370	0.4370	109.12	515	7	0.4370	103.12	24000	2	0
AAR0013598	02/10/1994	NY	2	10	-99	1965	212	B	0.4370	0.4370	102.00	212	B	0.5000	102.00	20000	2	1
16600B	02/07/1975	IL	2	10	0	1970	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
OT126	02/15/1975	MO	2	10	3	1971	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	20878	2	0
0720004A78	01/09/1978	MI	2	10	4	1977	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	20000	2	0
402161	01/24/1984	WI	2	10	5	1964	212	B	0.8750	0.8750	-99.00	212	B	0.8750	-99.00	11000	2	0
16600A	02/07/1975	IL	2	10	10	1968	515	7	0.4370	0.4370	102.00	515	7	0.5000	102.00	20000	2	1
BOAWN0309	03/02/1985	OH	2	10	10	1981	515	7	0.4370	0.4370	107.81	515	7	0.4370	106.00	18000	2	0
220183101	01/04/1983	Tx	2	10	30	1980	515	7	0.4370	0.4370	95.00	515	7	0.4370	95.00	13603	2	0
009	12/26/1987	MT	2	10	8	1985	209	L	0.5000	0.5000	102.00	209	L	0.5000	102.00	20497	1	1
AAR0009050	03/16/1987	BC	2	11	-99	1977	-99	-99	-99.0000	-99.0000	-99.00	-99	-99	-99.0000	-99.00	33997	2	0
AAR0009050	03/16/1987	BC	2	11	-99	1970	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33800	2	0

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)
- **-99** = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
403331	01/26/1982	WI	2	11	5	1974	515	7	0.4370	0.4370	103.25	515	7	0.4370	103.25	16158	2	0
AWN0219	02/03/1982	IL	2	12	0	1980	515	7	0.4370	0.4370	106.50	515	7	0.4370	102.00	18000	2	0
GC0400108	04/18/2000	TX	2	12	0	[illegible]	128	BN	0.6180	0.6180	117.87	128	BN	0.6870	117.87	33932	2	0
HN40	01/10/1979	IL	2	12	7	1967	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	20000	2	0
AAR0001823	01/07/1970	IL	2	12	10	1969	128	B	0.7790	0.7790	-99.00	128	B	0.8120	-99.00	17000	2	0
104422	02/03/1980	IL	2	13	0	1963	285	C	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	8000	2	0
134392	02/02/1979	IL	2	14	0	1964	212	B	0.4370	0.4370	88.37	212	B	0.4370	78.00	8221	2	0
79030	02/03/1979	MO	2	14	0	1971	285	C	0.4370	0.4370	89.12	285	C	0.4690	89.12	8163	2	0
AAR0006604	[illegible]	ON	2	14	0	1966	212	B	0.7030	0.8120	118.37	212	B	0.7030	104.25	34000	2	0
AAR0006579	[illegible]	ON	2	14	2	1980	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33800	2	1
AAR0013322	02/17/1993	PQ	2	14	4	-99	516	7	0.4370	0.4370	99.00	516	7	0.4370	99.00	14100	2	0
AAR0007688	11/29/1984	SK	2	14	5	1969	128	B	0.6250	0.6250	118.05	128	B	0.6870	118.05	33911	2	0
AAR0008323	03/08/1986	ON	2	14	5	1980	515	7	0.4370	0.4370	-99.00	515	7	0.4690	-99.00	21000	2	0
AAR0006605	02/28/1984	ON	2	14	6	1980	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33800	2	0
AAR0012973	01/21/1992	SK	2	14	6	1991	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	23644	2	0
TA6705	01/21/1978	WV	2	14	10	1967	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	20000	2	0
20078	02/08/1985	MS	2	15	-99	1968	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33800	2	0
AAR0008924	12/13/1982	MB	2	15	0	1963	212	B	0.9540	0.9540	102.37	212	B	0.7500	102.09	31230	2	0
AAR0008924	12/13/1982	MB	2	15	0	1978	128	B	0.7080	0.7080	114.58	128	B	0.7080	114.58	33553	2	0
AAR0008924	12/13/1982	MB	2	15	0	1964	212	B	0.7030	0.7990	118.37	212	B	0.7030	104.25	32890	2	1
AAR0008924	12/13/1982	MB	2	15	0	1962	212	B	0.9690	0.9690	122.06	212	B	0.7500	97.50	30235	2	0
AAR0006733	12/03/1984	AB	2	15	0	1980	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	14000	2	0
85219	12/24/1985	MO	2	15	0	1967	515	7	0.4370	0.4370	-99.00	515	7	0.5000	-99.00	21000	2	0
MN0235	04/01/1993	MN	2	15	0	1977	515	7	0.4370	0.4370	106.37	515	7	0.4370	102.00	16914	2	0
MN0235	04/01/1993	MN	2	15	0	1977	515	7	0.4370	0.4370	94.50	515	7	0.4370	94.50	14013	2	0
160177-A	01/14/1977	IN	2	15	2	1965	285	C	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	10000	2	0
NA7A91	01/28/1991	MN	2	15	2	1974	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	23582	2	0
ADT091	02/24/1977	MI	2	15	3	1975	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	27000	2	0
PO17	01/13/1975	OR	2	15	5	1969	128	B	0.7750	-97.0000	-97.00	-97	-97	0.7750	-97.00	17000	2	0
19692	02/01/1985	VT	2	15	5	1981	128	B	0.6030	0.6030	114.79	128	B	0.6030	114.79	34000	2	0
NA63	12/30/1992	MN	2	15	5	1980	515	7	0.4370	0.4370	94.50	515	7	0.4370	94.50	13612	2	0
0810002A78	01/12/1978	OH	2	15	15	1964	285	C	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	10000	2	0
160177-B	01/14/1977	IN	2	15	0	1965	212	B	0.8750	-97.0000	-97.00	-97	-97	0.9750	-97.00	11000	1	0
027701614	02/17/1977	KY	2	15	0	1942	115	-98	0.3750	-97.0000	-97.00	-97	-97	0.5000	-97.00	10000	1	0
D85040	02/06/1985	NY	2	16	5	1981	516	7	0.4370	0.4370	102.00	516	7	0.4370	102.00	16000	2	0
D85040	02/06/1985	NY	2	16	5	1978	515	7	0.4370	0.4370	102.00	515	7	0.4370	102.00	16000	2	0
19771	02/16/1982	IL	2	16	3	1962	212	B	-99.0000	-99.0000	104.00	212	B	-99.0000	104.00	20428	1	0
AAR0014285	01/29/1997	IA	2	17	-99	1993	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	29947	2	1
AAR0014285	01/29/1997	IA	2	17	-99	1966	128	B	0.6530	0.6530	112.00	128	B	0.6530	112.00	33500	2	0
10001A94	01/07/1994	PA	2	17	4	1993	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	23490	2	0
0340004B85	02/14/1985	NJ	2	18	0	1967	515	7	0.4370	0.4370	102.00	515	7	0.4370	102.00	20600	2	1
PS0018	01/11/1993	WA	2	18	3	1967	285	C	0.5000	0.5000	98.00	285	C	0.5000	98.00	20776	2	0
0830001A88	01/13/1988	IN	2	18	5	1968	515	7	0.4370	0.4370	102.00	515	7	0.5000	102.00	20000	2	0
0830001A88	01/13/1988	IN	2	18	5	1968	515	7	0.4370	0.4370	102.00	515	7	0.5000	102.00	21000	2	0
0830001A88	01/13/1988	IN	2	18	5	1966	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	20000	2	0
0830001A88	01/13/1988	IN	2	18	5	1966	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	20000	2	0
0830001A88	01/13/1988	IN	2	18	5	1968	515	7	0.4370	0.4370	102.00	515	7	0.4370	102.00	20000	2	0
0830001A88	01/13/1988	IN	2	18	5	1966	515	7	0.4370	0.4370	102.00	515	7	0.4370	102.00	21000	2	0
0830001A88	01/13/1988	IN	2	18	5	1971	515	7	0.4370	0.4370	108.00	515	7	0.4370	102.00	16000	2	0
20002	01/30/1994	PA	2	18	8	1982	128	B	0.4370	0.4370	114.37	516	7	0.4370	114.37	30600	2	1
19970	01/09/1984	IL	2	20	0	1975	515	7	0.5620	0.5620	94.50	515	7	0.5620	94.50	13617	2	1
0940004A	01/05/1990	IN	2	20	0	1973	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	17000	2	0
20884	02/08/1984	IL	2	20	2	1970	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	24000	2	0
CH158	02/27/1980	IL	2	20	3	1966	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	24645	2	0
1188NP205	11/26/1988	NE	2	20	3	1973	515	7	0.4370	0.4370	94.50	515	7	0.4370	94.50	14000	2	0
1188NP205	11/26/1988	NE	2	20	3	1982	515	7	0.4370	0.4370	98.62	515	7	0.4370	94.50	14000	2	0
T25A60	12/12/1975	OK	2	20	4	1972	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
16617	03/03/1975	KY	2	20	5	1968	515	7	0.4690	-97.0000	-97.00	-97	-97	0.5000	-97.00	22000	2	0
0310001B87	02/09/1987	PA	2	20	5	1973	515	7	0.4370	0.5620	95.00	515	7	0.4370	95.00	14000	2	1

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)
- **-99** = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
80001B97	02/20/1997	OH	2	20	5	1989	128	BN	0.7750	0.7750	100.44	128	BN	0.8120	100.44	17360	2	0
0100UT007	01/08/2000	NV	2	20	5	1994	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	23431	2	0
AAR0001887	02/19/1970	IL	2	20	0	1949	115	-98	0.5620	-99.0000	-99.00	115	-98	0.5620	-99.00	7022	1	1
1212	12/12/1976	IL	2	20	5	1962	285	C	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	10000	1	0
1212	12/12/1976	IL	2	20	5	1951	285	C	0.5000	0.5000	86.25	285	C	0.5000	86.25	9935	1	0
1212	12/12/1976	IL	2	20	5	1954	285	C	0.5000	-99.0000	-99.00	-99	-99	0.5000	-99.00	12167	1	1
AF60901	02/04/1978	IL	2	20	5	1955	285	C	0.6870	0.6870	88.50	285	C	0.6870	88.50	11069	1	1
200280102	02/16/1980	TX	2	20	6	1958	285	C	0.5000	0.5000	99.00	285	C	0.5620	99.00	18199	1	0
0420003L76	12/10/1976	NY	2	21	2	1976	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	23703	2	1
79243	01/16/1979	MO	2	22	0	1968	515	7	0.4370	0.4370	102.00	515	7	0.5000	102.00	20636	2	1
9412H0795	12/23/1994	MN	2	22	1	1990	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	23592	2	0
G2572	02/02/1995	WI	2	22	2	1979	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	16759	2	0
080295	02/16/1995	IA	2	22	4	1981	515	7	0.4370	0.4370	109.62	515	7	0.4370	106.00	23520	2	0
SD0397100	03/03/1997	MN	2	22	5	1996	128	B	0.4370	0.4370	116.25	128	B	0.4370	116.25	19636	2	0
130278	02/10/1978	IL	2	22	2	1975	128	B	0.4370	0.4370	110.25	128	B	0.4370	106.00	20829	1	0
AAR0008350	03/20/1986	MB	2	23	-99	1971	128	B	0.6250	0.6250	-99.00	128	B	0.6870	-99.00	33893	2	0
ACO49	02/05/1976	IL	2	23	0	1972	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	21000	2	0
AAR0006200	02/19/1979	ON	2	24	-99	1969	285	C	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	20000	2	0
AAR0006323	07/10/1985	MB	2	24	-99	1971	515	7	0.4370	0.4370	78.00	516	7	0.4370	78.00	8295	2	1
AAR0005129	04/06/1974	MB	2	24	-99	1962	285	C	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	12000	1	0
AAR0006400	01/07/1969	IL	2	24	-99	1947	285	C	0.6870	0.6870	85.00	115	-98	0.6870	85.00	10500	1	0
AAR0006400	01/07/1969	IL	2	24	-99	1946	-99	-99	-99.0000	-99.0000	77.00	-99	-99	-99.0000	77.00	8000	1	0
AAR0012186	02/02/1990	KS	2	25	-99	1973	128	B	0.4370	0.4370	118.02	515	7	0.4370	115.12	30000	2	1
32115124	11/26/1975	TX	2	25	0	1969	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	20800	2	0
141281102	11/28/1981	KS	2	25	0	1978	515	7	0.4370	0.4370	108.00	515	7	0.4370	102.00	24000	2	0
0182ID207	01/23/1982	ID	2	25	0	1969	515	7	0.4370	0.4370	105.12	515	7	0.5000	105.12	13619	2	1
0182ID207	01/23/1982	ID	2	25	0	1969	515	7	0.4370	0.4370	105.12	515	7	0.5000	105.12	14000	2	0
100252	01/05/1985	IL	2	25	0	1969	128	B	0.6250	0.6250	118.05	128	B	0.6870	118.05	33942	2	0
AF5002	02/19/1988	IL	2	25	0	1968	515	7	0.4370	0.4370	95.12	515	7	0.5000	95.12	13000	2	0
ACC265	12/01/1975	OH	2	25	2	1965	285	C	0.5000	0.5000	93.50	285	C	0.5000	87.50	10422	2	0
365	10/26/1997	MT	2	25	3	1966	128	B	0.6870	0.6870	117.90	128	B	0.6870	117.90	33585	2	0
AAR0001206	12/15/1968	IL	2	25	5	1968	515	7	0.4690	-99.0000	-99.00	515	7	0.5000	-99.00	26766	2	1
751122	11/12/1975	WI	2	25	5	1967	285	C	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	10000	2	0
20001C93	03/09/1993	OH	2	25	5	1987	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	16722	2	1
20001C93	03/09/1993	OH	2	25	5	1987	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	16745	2	0
20001C93	03/09/1993	OH	2	25	5	1980	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	20583	2	0
AF8015	02/29/1996	IL	2	25	5	1995	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	17574	2	0
781155	11/24/1978	MN	2	25	6	1969	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	8000	2	0
1128	11/28/1975	IL	2	25	7	1970	515	7	0.4370	0.4370	105.00	515	7	0.4690	105.00	20431	2	0
AF59680	01/25/1977	IL	2	25	10	1971	515	7	0.4370	0.437?	109.12	515	7	0.4370	103.12	20587	2	1
AAR0007285	02/17/1985	ON	2	25	25	1981	516	7	0.5000	0.5000	95.00	516	7	0.5000	95.00	13000	2	0
AAR0007285	02/17/1985	ON	2	25	25	1981	516	7	0.5000	0.5000	95.00	516	7	0.5000	95.00	13000	2	0
32115124	11/26/1975	TX	2	25	0	1956	285	C	0.6870	-97.0000	-97.00	-97	-97	0.6870	-97.00	11000	1	0
D2	01/24/1979	TX	2	25	0	1957	285	C	0.7500	-97.0000	-97.00	-97	-97	0.7500	-97.00	6000	1	0
0920007L77	12/19/1977	IN	2	25	2	1948	115	-98	0.3750	0.3750	86.50	115	-98	0.5000	86.50	10102	1	1
AAR0001206	12/15/1968	IL	2	25	5	1967	285	C	0.4370	0.4370	77.00	285	C	0.5000	77.00	8000	1	0
1278WY212	12/28/1978	CO	2	25	5	1954	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	19000	1	0
AAR0010805	01/07/1984	AB	2	26	0	1981	516	7	0.4490	0.4490	113.12	516	7	0.4370	113.12	30100	2	0
AAR0010805	01/07/1984	AB	2	26	0	1966	128	B	0.6920	0.6920	118.62	128	B	0.6000	102.80	34000	2	0
AAR0010805	01/07/1984	AB	2	26	0	1971	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33800	2	0
AAR0010805	01/07/1984	AB	2	26	0	1966	128	A	0.6870	0.6870	117.92	128	A	0.6870	117.92	33500	2	0
1287ID204	12/08/1987	ID	2	26	0	1977	128	B	0.5620	0.5620	119.00	128	B	0.5620	119.00	34000	2	0
30003	01/23/1997	IN	2	26	0	1990	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	25851	2	0
30003	01/23/1997	IN	2	26	0	1990	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	25851	2	0
010005042	01/30/2000	NC	2	26	6	1985	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	20599	2	0
010005042	01/30/2000	NC	2	26	6	1969	515	7	0.4370	0.4370	108.00	515	7	0.4370	102.00	23500	2	0
AAR0003072	02/03/1972	IL	2	26	0	1949	115	-98	0.5000	-99.0000	-99.00	-99	-99	0.5000	-99.00	10000	1	1
16622	03/08/1975	KY	2	26	2	1952	285	C	0.3750	0.3750	77.00	285	C	0.5000	77.00	8040	1	1
418002	02/24/1978	WI	2	26	4	1950	115	-98	0.3750	0.3750	86.50	115	-98	0.5000	86.50	10135	1	1

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)

-99 = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
AF2655	02/08/1984	IL	2	26	10	1955	285	C	0.4370	0.4370	86.50	285	C	0.5000	86.50	10213	1	1
AF1958A	02/27/1982	IL	2	27	0	1967	285	C	0.4370	0.4370	78.00	285	C	0.5000	78.00	8000	2	0
T280284009	02/05/1984	MI	2	27	0	1978	516	7	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	13000	2	0
1078WY210	10/23/1978	CO	2	27	5	1973	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	24000	2	0
AF8818	11/19/1997	IL	2	27	5	1968	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33800	2	0
AF8818	11/19/1997	IL	2	27	5	1973	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33800	2	0
AAR0005996	02/09/1984	SK	2	28	-99	1969	128	B	0.6940	0.6940	119.00	128	B	0.6940	119.00	34000	2	0
H1519	01/15/1979	TX	2	28	0	1971	128	B	0.6250	0.6250	118.75	128	B	0.6560	118.75	33662	2	0
H1519	01/15/1979	TX	2	28	0	1969	128	B	0.6250	0.6250	118.75	128	B	0.6560	118.75	33600	2	0
AAR0006825	12/21/1984	BC	2	28	2	1968	128	B	0.6030	0.6030	114.79	128	B	0.6030	114.79	33900	2	0
0430005J76	10/27/1976	NY	2	28	3	1965	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	20477	2	1
19772A	02/19/1982	IL	2	28	4	1972	128	B	0.7790	0.7790	100.75	128	B	0.8120	100.75	17402	2	0
0420008L78	12/27/1978	NY	2	28	5	1969	285	C	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	8000	2	0
B84283	11/13/1984	NY	2	28	5	1971	515	7	0.5620	0.5620	94.50	515	7	0.5620	94.50	13608	2	0
PS0203-B	02/24/1993	WA	2	28	5	1989	516	7	0.4490	0.4490	113.10	516	7	0.4370	113.10	25635	2	0
49705	04/07/1997	IL	2	28	6	1981	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	17545	2	0
330273	02/29/1984	LA	2	28	4	1968	516	7N	0.9370	0.9370	94.50	516	7N	0.9370	94.50	18000	1	0
781230	12/17/1978	WI	2	28	5	-99	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	-97	-99	0
AX1L85	12/14/1985	TX	2	29	0	1960	212	B	0.6870	0.6870	83.62	212	B	0.6870	83.62	11000	2	0
087634	02/07/1996	TN	2	29	0	1968	515	7	0.4370	0.4370	78.00	515	7	0.4370	78.00	10000	2	1
F4832	11/13/1982	OH	2	29	1	1981	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	18000	2	0
0530001C77	03/04/1977	PA	2	29	2	1973	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	26692	2	0
D9435	02/03/1981	GA	2	29	3	1979	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4680	-97.00	24000	2	0
D4727	12/27/1979	IL	2	29	5	1977	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	15000	2	0
AAR0013636	10/16/1994	AB	2	30	-99	1969	128	B	0.6030	0.6030	114.79	128	B	0.6030	114.79	33800	2	0
AAR0013636	10/16/1994	AB	2	30	-99	1974	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33808	2	0
AAR0013636	10/16/1994	AB	2	30	-99	1974	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33820	2	0
AAR0013636	10/16/1994	AB	2	30	-99	1965	212	B	0.7130	0.7130	118.37	212	B	0.6330	104.25	33500	2	0
AAR0013636	10/16/1994	AB	2	30	-99	1968	128	B	0.6030	0.6030	114.79	128	B	0.6030	114.79	33900	2	0
310006CA77	01/27/1977	DE	2	30	0	-99	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	34000	2	0
0179WY206	01/14/1979	WY	2	30	0	1973	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	24000	2	0
CH19	01/06/1980	IL	2	30	0	1978	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	24000	2	0
F5796	03/13/1983	AL	2	30	0	1970	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	16000	2	0
BOACH0024	01/18/1987	OH	2	30	0	1986	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	17641	2	0
20407	02/10/1991	IL	2	30	0	1985	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	17600	2	0
D80007	02/28/1980	IL	2	30	2	1978	128	B	0.5620	0.5620	112.87	128	B	0.5940	112.87	25150	2	1
0186KC206	01/18/1986	MO	2	30	2	1980	285	C	0.5620	0.5620	88.81	285	C	0.5620	88.81	13000	2	0
AAR0005901	12/11/1974	NE	2	30	3	1971	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
1276ID052	12/21/1976	ID	2	30	3	1973	128	B	0.7500	-97.0000	-97.00	-97	-97	0.7500	-97.00	34000	2	0
83209	11/25/1983	MO	2	30	3	1980	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	21000	2	0
861214	12/20/1986	IL	2	30	3	1978	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	24000	2	0
30001	01/14/1993	IN	2	30	3	1970	515	7	0.4370	0.4370	113.06	515	7	0.4690	113.06	22897	2	0
CH79	02/22/1984	IL	2	30	4	1976	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
0400CB009	04/07/2000	IA	2	30	5	1997	128	BN	0.5620	0.5620	118.75	128	BN	0.5620	118.75	33623	2	0
0400CB009	04/07/2000	IA	2	30	5	1998	128	BN	0.5620	0.5620	117.87	128	BN	0.6030	117.87	33800	2	0
212978	12/08/1978	CA	2	30	5	1974	515	7	0.4370	0.4370	108.37	515	7	0.4370	102.00	16842	2	1
212978	12/08/1978	CA	2	30	5	1975	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	16000	2	0
MRL064	02/08/1990	MT	2	30	5	1968	515	7	0.4690	0.4690	113.06	515	7	0.5000	113.06	22743	2	0
D06229	01/23/1988	OH	2	30	7	1975	515	7	0.4370	0.5620	106.00	515	7	0.4370	106.00	19346	2	0
118309604	11/11/1983	TN	2	30	8	1970	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	16000	2	0
TA5606	01/17/1975	OH	2	30	10	1971	515	7	0.4370	0.4370	95.00	515	7	0.4370	95.00	12374	2	1
16	01/29/1995	AZ	2	30	10	1978	515	7	0.5620	0.5620	100.62	515	7	0.5620	100.62	13684	2	0
20002D97	04/08/1997	PA	2	30	10	1994	128	BN	0.5620	0.5620	117.87	128	BN	0.6030	117.87	25800	2	0
AAR0001359	03/12/1969	IL	2	30	0	1919	115	-98	0.3750	-97.0000	-97.00	-97	-97	0.5000	-97.00	10000	1	0
AAR0001367	03/18/1969	PQ	2	30	0	1919	115	-98	0.3750	0.3750	-99.00	115	-98	0.5000	-99.00	8100	1	1
AAR0001367	03/18/1969	PQ	2	30	0	1919	115	-98	0.3750	0.3750	-99.00	115	-98	0.5000	-99.00	8000	1	1
030475	04/04/1975	IL	2	30	0	1954	285	C	0.4370	0.4370	78.62	285	C	0.5000	78.62	8072	1	1
0920002B83	02/09/1983	IN	2	30	0	1967	285	C	0.4370	0.4370	78.00	285	C	0.4370	78.00	6220	1	1
EA9	03/25/1985	WI	2	30	2	1955	285	C	0.6870	0.6870	85.00	285	C	0.6870	85.00	11000	1	0

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)
- **-99** = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
AAR0000429	01/31/1967	IL	2	30	5	1925	115	-98	0.3750	-97.0000	-97.00	-97	-97	0.5000	-97.00	8000	1	0
AAR0005814	11/15/1974	IL	2	30	5	1956	285	C	0.4370	0.4370	77.62	285	C	0.5000	77.62	8137	1	1
AAR0010429	12/21/1974	IA	2	30	5	1950	285	C	0.3750	0.5000	77.00	285	C	0.5000	77.00	8000	1	0
761109	11/03/1976	MI	2	30	5	1956	285	C	0.6870	-97.0000	-97.00	-97	-97	0.6870	-97.00	11000	1	0
AAR0000486	03/23/1967	ON	2	30	20	1944	285	C	0.7030	0.7030	-99.00	285	C	0.7030	-99.00	10500	1	0
10007063	01/25/2000	OH	2	31	1	1991	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	23596	2	0
087212	01/04/1996	AL	2	31	2	1972	285	C	0.5620	0.5620	89.12	285	C	0.5620	89.12	13502	2	0
PA2308	12/18/1991	WA	2	31	5	1991	128	BN	0.7280	0.7280	117.87	128	BN	0.7810	117.87	33960	2	0
341624	01/19/1985	MO	2	31	7	1974	515	7	0.4370	0.4370	103.25	515	7	0.4370	103.25	16000	2	0
341624	01/19/1985	MO	2	31	7	1969	515	7	0.4370	0.4370	109.00	515	7	0.5000	108.00	23000	2	0
0830003K82	11/16/1982	IN	2	31	8	1981	515	7	0.4370	0.4370	102.00	515	7	0.4370	102.00	16343	2	1
0830003K82	11/16/1982	IN	2	31	8	1978	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	17000	2	0
0830003K82	11/16/1982	IN	2	31	8	1978	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	17000	2	0
OT226	03/27/1975	IL	2	31	-99	1953	285	C	0.4370	-99.0000	-99.00	-99	-99	0.5000	-99.00	10000	1	1
AAR0000080	11/21/1967	NY	2	31	15	1951	240	S	0.3120	0.4370	77.00	240	S	0.5000	77.00	7346	1	1
AAR0005841	11/22/1974	WA	2	32	0	1973	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	-97	2	0
AAR0005841	11/22/1974	WA	2	32	0	1972	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	21000	2	0
AF63290	03/02/1979	IL	2	32	0	1977	515	7	0.4370	0.4370	100.62	515	7	0.4690	100.62	15000	2	0
DK0300104	03/12/2000	MN	2	32	0	1986	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	16423	2	0
AAR0008135	10/08/1985	SK	2	32	1	1966	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	20000	2	0
340290103	02/21/1990	TX	2	32	3	1965	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	20000	2	0
751280	12/26/1975	KS	2	32	4	1965	128	B	0.6530	0.6530	112.00	128	B	0.6530	112.00	34000	2	0
AAR0008655	10/26/1982	AB	2	32	4	1968	128	B	0.6940	0.6940	119.00	128	B	0.6940	119.00	33000	2	0
AAR0010882	04/28/1983	AB	2	32	4	1966	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33500	2	0
AAR0010883	04/28/1983	AB	2	32	5	1967	128	B	0.5990	0.6910	118.62	128	B	0.5990	102.80	34000	2	0
AAR0010883	04/28/1983	AB	2	32	5	1968	128	B	0.6250	0.6250	119.00	128	B	0.6250	119.00	33000	2	0
110	01/26/1988	AB	2	32	5	1980	516	7	-99.0000	-99.0000	-99.00	516	7	-99.0000	-99.00	21000	2	0
110	01/26/1988	AB	2	32	5	1981	516	7	0.4440	0.4440	112.00	516	7	0.4440	112.00	21000	2	0
110	01/26/1988	AB	2	32	5	1981	516	7	0.4440	0.4440	112.00	516	7	0.4440	112.00	21000	2	0
110	01/26/1988	AB	2	32	5	1981	516	7	0.4440	0.4440	112.00	516	7	0.4440	112.00	21000	2	0
110	01/26/1988	AB	2	32	5	1979	516	7	0.4370	0.4370	102.00	516	7	0.4370	102.00	16000	2	0
110	01/26/1988	AB	2	32	5	1979	516	7	0.4370	0.4370	102.00	516	7	0.4370	102.00	16000	2	0
230282106	02/05/1982	TX	2	32	10	1977	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	24000	2	0
230282106	02/05/1982	TX	2	32	10	1975	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	24000	2	0
T920388019	03/21/1988	IL	2	32	10	1967	285	C	0.4370	0.4370	105.12	285	C	0.5000	105.12	10253	2	0
D5963	03/10/1980	TN	2	32	4	1967	209	L	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	20000	1	1
16615	03/02/1975	TN	2	32	5	1952	285	C	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	8000	1	0
D87011	01/07/1987	PA	2	32	5	1960	285	C	0.6870	0.6870	88.50	285	C	0.6870	88.50	11090	1	1
AF5574	04/23/1989	IL	2	33	-99	1967	128	B	0.6530	0.6530	112.00	128	B	0.6530	112.00	31300	2	1
CH128	03/22/1984	IL	2	33	0	1973	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	24000	2	0
SA51L89	12/30/1989	IL	2	33	0	1981	516	7	0.4370	0.4370	98.62	516	7	0.4370	94.50	14000	2	0
028016712	02/09/1980	GA	2	33	4	1975	285	C	0.5620	0.5620	89.12	285	C	0.5620	89.12	13175	2	0
448769	01/15/1991	MO	2	33	4	1979	128	B	0.5620	0.5620	112.87	128	B	0.5930	112.87	24838	2	0
AAR0008795	11/20/1982	MB	2	33	-99	1965	285	C	-99.0000	-99.0000	-97.00	-97	-97	-99.0000	-97.00	6000	1	0
0530006C80	03/17/1980	PA	2	33	6	1957	209	L	0.7800	-97.0000	-97.00	-97	-97	0.7020	-97.00	10000	1	0
PA0024	01/16/1993	WA	2	34	2	1980	515	7	0.4370	0.4370	100.62	515	7	0.4690	100.62	13501	2	0
X5684	11/22/1984	TX	2	34	3	1966	212	B	0.6880	-97.0000	-97.00	-97	-97	0.6880	-97.00	12000	2	0
SP0231	04/12/1993	WA	2	34	4	1970	515	7	0.4690	0.4690	113.06	515	7	0.5000	113.06	22410	2	0
SP0231	04/12/1993	WA	2	34	4	1968	515	7	0.4690	0.4690	113.06	515	7	0.5000	113.06	22750	2	0
1100TC019	11/28/2000	MN	2	34	5	1975	515	7	0.4370	0.4370	89.00	515	7	0.4690	89.00	8163	2	0
F5381	01/25/1983	MS	2	34	5	1976	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	21000	2	0
0499NP007	04/11/1999	NE	2	34	5	1980	515	7	0.4370	0.4370	105.00	515	7	0.4690	105.00	16368	2	0
CA27	05/08/1979	WI	2	34	10	1969	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	13000	2	0
0720005J76	10/17/1976	MI	2	34	3	1942	212	B	0.6870	0.6870	-99.00	212	B	0.6870	-99.00	6000	1	0
0720005J76	10/17/1976	MI	2	34	3	1966	212	B	0.4370	0.4370	103.12	212	B	0.5000	103.12	21129	1	0
017709602	01/29/1977	NC	2	34	8	1947	115	-98	0.6870	0.6870	-97.00	115	-98	0.6870	-97.00	6000	1	0
0930001D77	04/21/1977	OH	2	35	-99	1969	515	7	0.4690	-97.0000	-97.00	-97	-97	0.5000	-97.00	20000	2	0
EA17	03/28/1978	WI	2	35	-99	1966	285	C	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	13000	2	0
1100SL026	11/26/2000	IL	2	35	0	1992	128	B	0.4370	0.4370	110.25	128	B	0.4690	110.25	30028	2	0

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)
- **-99** = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
D617	10/14/1976	MI	2	35	0	1967	128	B	0.6530	-97.0000	-97.00	-97	-97	0.6530	-97.00	33000	2	0
117606027	11/07/1976	IN	2	35	0	1967	285	C	0.5000	0.5000	98.00	285	C	0.5000	98.00	21560	2	1
18586	11/08/1978	TN	2	35	0	1966	212	B	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	17000	2	0
84002	02/03/1984	IL	2	35	0	1979	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	27000	2	0
Ax67N	12/09/1986	TX	2	35	0	1970	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	20902	2	0
RE872	12/23/1987	AL	2	35	0	1970	515	7	0.4370	0.4370	109.00	515	7	0.5000	108.00	24000	2	0
RE872	12/23/1987	AL	2	35	0	1980	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	23529	2	0
GT0339	02/25/1992	IA	2	35	0	1990	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	17574	2	0
AF8465	01/02/1997	IL	2	35	0	1994	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	20612	2	0
0530001A90	01/24/1990	PA	2	35	2	1965	212	B	0.4370	0.4370	105.12	212	B	0.5000	105.12	23900	2	0
017818007	01/08/1978	AL	2	35	3	1967	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33845	2	0
0530002J88	10/10/1988	OH	2	35	3	1971	515	7	0.4370	0.4370	108.00	515	7	0.5000	108.00	21000	2	0
0530002J88	10/10/1988	OH	2	35	3	1975	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	20665	2	1
AAR0010450	12/09/1975	IL	2	35	4	1969	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
17378	11/03/1976	IL	2	35	4	1969	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	20000	2	0
2121478	12/09/1978	CA	2	35	4	1978	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	21000	2	0
20235	03/29/1988	IL	2	35	4	1984	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	18000	2	0
20235	03/29/1988	IL	2	35	4	1984	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	18000	2	0
20235	03/29/1988	IL	2	35	4	1986	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	18000	2	0
321280101B	12/09/1980	CA	2	35	5	1969	515	7	0.4690	0.4690	113.06	515	7	0.5000	113.06	23000	2	0
128206022	12/14/1982	IL	2	35	5	1961	212	B	0.6250	-97.0000	-97.00	-97	-97	0.6250	-97.00	20000	2	0
80002BK96	11/20/1996	IN	2	35	5	1988	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	23569	2	0
1098CE021	10/28/1998	WY	2	35	5	1993	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	23497	2	0
AF3156	12/10/1984	IL	2	35	6	1977	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	14000	2	0
K0077	01/23/1987	AR	2	35	6	1978	128	B	0.5620	0.5620	114.87	128	B	0.5620	114.87	34000	2	0
96110794	11/16/1996	MN	2	35	6	1985	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	17667	2	0
780454	04/19/1978	NE	2	35	10	1972	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	23000	2	0
PS0041A	03/10/1995	WA	2	35	10	1967	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33487	2	0
T120287001A	02/08/1987	OH	2	35	20	1969	515	7	0.4370	0.4370	105.12	515	7	0.4370	105.12	14000	2	0
0930001D77	04/21/1977	OH	2	35	-99	1950	212	B	0.8750	0.8750	85.00	212	B	0.8750	85.00	10000	1	0
1282WY203	12/12/1982	WY	2	35	0	1967	516	7N	1.0000	1.0000	97.00	516	7N	1.0000	97.00	18000	1	0
0420001C87	03/01/1987	NY	2	35	5	1981	209	L	0.6870	0.6870	108.00	209	L	0.7410	108.00	21000	1	1
AAR0005845	11/25/1974	BC	2	36	-99	1966	212	B	0.4370	0.4370	105.12	212	B	0.4370	105.12	13900	2	1
AAR0005969	01/08/1975	PQ	2	36	-99	1973	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	24000	2	0
AAR0006734	12/01/1984	BC	2	36	-99	1965	128	B	0.6530	0.6530	112.00	128	B	0.6530	112.00	34000	2	0
AF2044	04/10/1982	IL	2	36	0	1966	212	B	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	8000	2	0
108402601	10/02/1984	TN	2	36	2	1972	515	7	0.4370	0.4370	108.00	515	7	0.4370	102.00	24000	2	0
108402601	10/02/1984	TN	2	36	2	1975	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
AF4317	12/20/1986	IL	2	36	4	1981	515	7	0.4370	0.4370	100.62	515	7	0.4690	100.62	14000	2	0
802143	02/17/1998	NJ	2	36	4	1995	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	20575	2	0
AF59961	04/06/1977	IL	2	36	10	1970	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	23000	2	0
4266	01/20/1981	OH	2	36	10	1970	515	7	0.4480	0.4480	113.00	515	7	0.5620	112.00	31067	2	1
GT0887	12/15/1990	IL	2	36	10	1975	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	20831	2	0
AAR0013659	11/05/1994	MB	2	36	10	1969	128	B	0.6030	0.6030	114.79	128	B	0.6030	114.79	33900	2	0
70002C95	03/06/1996	NY	2	36	13	1977	128	B	0.5620	0.5620	114.87	128	B	0.5620	114.87	34000	2	1
AAR0005969	01/08/1975	PQ	2	36	-99	1974	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	23000	1	0
T25A423	01/02/1980	OK	2	36	1	1952	285	C	0.6870	-97.0000	-97.00	-97	-97	0.6870	-97.00	11000	1	0
17374	11/02/1976	TN	2	36	4	-99	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	-97	-99	0
Y1529	12/29/1976	GA	2	36	12	-99	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	-97	-99	0
049622014	04/11/1996	MD	2	37	2	1974	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	20577	2	1
AAR0014563	11/14/1997	MO	2	37	5	1974	515	7	0.4370	0.4370	109.12	515	7	0.4370	103.12	20730	2	0
0920003D80	04/27/1980	IN	2	37	49	1975	515	7	0.4370	0.4370	109.12	515	7	0.4370	103.12	24000	2	0
0920003D80	04/27/1980	IN	2	37	49	1952	285	C	0.9370	-97.0000	-97.00	-97	-97	0.9370	-97.00	10000	1	0
0920003D80	04/27/1980	IN	2	37	49	1964	209	L	0.6250	0.6250	78.00	209	L	0.6250	78.00	8037	1	0
AAR0000021	02/06/1965	IL	2	37	0	1965	-99	-99	-99.0000	-99.0000	-99.00	-99	-99	-99.0000	-99.00	-99	-99	0
0420013C78	03/15/1978	NY	2	38	0	1965	212	B	0.8120	0.8120	116.37	212	B	0.7190	104.56	33620	2	1
48813	03/15/1985	VA	2	38	0	1980	515	7	0.4370	0.4370	100.62	515	7	0.4690	100.62	14000	2	0
CH731	12/08/1986	IL	2	38	0	1983	515	7	-99.0000	-99.0000	-99.00	515	7	-99.0000	-99.00	18000	2	0
R74765	02/02/1992	NC	2	38	2	1971	285	C	0.4370	0.4370	105.00	515	7	0.4690	105.00	16369	2	0

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)
- **-99** = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
20757	02/17/1995	IL	2	38	3	1993	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	25603	2	0
PA0135	01/26/1990	WA	2	38	4	1979	515	7	0.4370	0.4370	105.00	515	7	0.4690	105.00	16000	2	0
T10A6	02/23/1975	TN	2	38	5	1965	285	C	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	8000	2	0
1920300006	03/07/1976	NC	2	38	5	1974	516	B	0.4370	0.4370	108.00	516	7	0.6250	108.00	26000	2	0
20184	12/23/1986	MS	2	38	5	1966	212	B	0.4370	0.4370	98.12	212	B	0.4370	98.12	16236	2	0
ME40	02/07/1983	TN	2	38	7	1966	285	C	0.5000	0.5000	98.00	285	C	0.5000	98.00	13446	2	0
17085	04/25/1976	IL	2	38	0	1962	285	C	0.5000	0.5000	86.50	285	C	0.5000	86.50	10071	1	0
ILWR7626	04/05/1977	IL	2	38	5	1952	285	C	0.6870	0.6870	85.00	285	C	0.6870	85.00	10979	1	1
AAR0010490	10/30/1976	IL	2	39	-99	1965	212	B	0.4370	0.4370	78.00	212	B	0.4370	78.00	10000	2	0
NE0064	02/22/1996	NE	2	39	1	1989	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	25781	2	0
ACT317	11/23/1978	IL	2	39	5	1971	128	B	0.4370	0.4370	112.00	515	7	0.4370	112.00	30128	2	1
810511	05/09/1981	IA	2	39	5	1971	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	17000	2	0
1297KC008	12/27/1997	KS	2	39	6	1991	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	20408	2	0
1297KC008	12/27/1997	KS	2	39	6	1991	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	20408	2	0
810511	05/09/1981	IA	2	39	5	-99	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	-97	-99	0
AAR0003851	12/29/1972	IL	2	40	-99	1967	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	21000	2	0
AAR0003851	12/29/1972	IL	2	40	-99	1967	212	B	0.4370	0.4370	104.00	212	B	0.4370	104.00	20445	2	0
AAR0008085	09/26/1985	BC	2	40	-99	1967	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33448	2	0
1188TX202	11/10/1988	OK	2	40	-99	1971	515	7	0.4370	0.4370	108.00	515	7	0.5000	108.00	20665	2	0
12119102	11/21/1979	KS	2	40	0	1974	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	24000	2	0
AWN2145	12/03/1979	OH	2	40	0	1971	515	7	0.4370	0.4370	105.00	515	7	0.4690	105.00	20000	2	0
0581ID206	05/30/1981	ID	2	40	0	1978	515	7	0.4370	0.4370	108.66	515	7	0.4370	106.00	20955	2	0
AF2698	03/15/1984	IL	2	40	0	1972	515	7	0.4370	0.5620	103.25	515	7	0.4370	103.25	16169	2	1
AF2698	03/15/1984	IL	2	40	0	1971	515	7	0.4370	0.4370	105.00	515	7	0.4690	105.00	16389	2	0
128505613 A	12/15/1985	SC	2	40	0	1974	240	S	0.1920	0.1920	101.00	240	S	0.3120	98.00	20000	2	0
APR2897	04/12/1997	IL	2	40	0	1995	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	25498	2	0
AAR0010457	01/24/1976	MD	2	40	2	1972	128	B	0.7750	-97.0000	-97.00	-97	-97	0.8120	-97.00	17000	2	0
121080102	10/29/1980	KS	2	40	2	1979	128	B	0.5620	0.5620	112.87	128	B	0.5930	112.87	24850	2	0
AOH2228	11/10/1983	OH	2	40	2	1979	128	B	0.7870	-97.0000	-97.00	-97	-97	0.8120	-97.00	17000	2	0
W1594	02/02/1984	TX	2	40	2	1971	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	20861	2	0
W1594	02/02/1984	TX	2	40	2	1969	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	21000	2	0
85216	12/26/1985	LA	2	40	3	1967	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33723	2	0
R0875	11/23/1995	KS	2	40	3	1989	128	B	0.4370	0.4370	119.12	516	7	0.4690	119.12	30000	2	0
050592	04/07/2000	NJ	2	40	3	1989	128	B	0.4370	0.4370	110.25	128	B	0.4690	110.25	23475	2	0
AAR0003988	03/13/1973	IL	2	40	4	1963	128	B	0.6250	-97.0000	-97.00	-97	-97	0.6870	-97.00	32000	2	0
ILWR7618	04/04/1977	IA	2	40	4	1973	128	B	0.4370	0.4370	118.62	515	7	0.4370	115.12	30136	2	1
ILWR7618	04/04/1977	IA	2	40	4	1969	128	B	0.4370	0.4370	118.62	128	B	0.4370	115.12	30036	2	1
771158	11/23/1977	IA	2	40	4	1977	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
940003K83A	11/07/1983	OH	2	40	4	1980	515	7	0.4490	0.4490	112.87	515	7	0.5000	112.87	27000	2	0
940003K83B	11/07/1983	OH	2	40	4	1968	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	21000	2	0
018801005	01/03/1988	GA	2	40	4	1980	128	B	0.4370	0.4370	112.00	515	7	0.4370	112.00	30039	2	1
9310H0749	10/17/1993	MN	2	40	4	1968	515	7	0.4370	0.4370	105.12	515	7	0.5000	105.12	13645	2	0
G2465	10/26/1994	WI	2	40	4	1969	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33800	2	0
449520	12/11/1995	MO	2	40	4	1995	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	23630	2	0
019707018	01/22/1997	KY	2	40	4	1982	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	20865	2	0
80341	11/11/1980	IL	2	40	5	1975	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	23000	2	0
SF172B	04/09/1984	KS	2	40	5	1970	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	20873	2	0
0189VB206	01/24/1989	AR	2	40	5	1984	515	7	0.4370	0.4370	100.62	515	7	0.4690	100.62	13000	2	0
FW1354	11/10/1990	OK	2	40	5	1989	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	23664	2	0
PS0140	10/28/1994	WA	2	40	5	1984	515	7	0.4370	0.4370	105.00	515	7	0.4690	105.00	16371	2	0
141194100	11/26/1994	CA	2	40	5	1969	128	B	0.6250	0.6250	118.05	128	B	0.6870	118.05	33993	2	0
119507032	11/30/1995	KY	2	40	5	1980	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	23581	2	0
70002ALBAN	05/16/1997	NY	2	40	5	1988	128	BN	0.7870	0.7870	102.00	128	BN	0.7870	102.00	17368	2	0
1078NP201	10/23/1978	NE	2	40	8	1976	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	16000	2	0
AF60039	04/28/1977	IL	2	40	10	1969	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	23000	2	0
AAR0008370	11/06/1978	ON	2	40	10	1975	516	7	0.5000	0.5000	94.50	516	7	0.5000	94.50	13750	2	1
AAR0008370	11/06/1978	ON	2	40	10	1967	285	C	0.5000	0.5000	98.00	285	C	0.5000	98.00	13700	2	1
AAR0008370	11/06/1978	ON	2	40	10	1967	285	C	0.5000	0.5000	98.00	285	C	0.5000	98.00	13700	2	1
AAR0008370	11/06/1978	ON	2	40	10	1967	285	C	0.5000	0.5000	98.00	285	C	0.5000	98.00	13700	2	1

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)
- **-99** = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
AAR0008370	11/06/1978	ON	2	40	10	1967	285	C	0.5000	0.5000	105.00	285	C	0.5000	105.00	14000	2	0
AAR0008370	11/06/1978	ON	2	40	10	1973	516	7	0.5000	0.5000	95.00	516	7	0.4370	95.00	13700	2	1
AAR0008370	11/06/1978	ON	2	40	10	1977	516	7	0.5000	0.5000	95.00	516	7	0.4370	95.00	13662	2	1
AAR0010989	11/23/1983	PQ	2	40	11	1977	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	16000	2	0
AAR0010989	11/23/1983	PQ	2	40	11	1980	516	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	16000	2	0
AAR0010989	11/23/1983	PQ	2	40	11	1964	212	B	0.8120	0.8120	116.37	212	B	0.7190	104.56	33500	2	0
AAR0003144	03/11/1972	IL	2	40	15	1971	515	7	0.4370	0.4370	108.00	515	7	0.5000	108.00	20660	2	1
AAR0003245	12/29/1972	IL	2	40	-99	1957	285	C	0.6870	0.6870	-99.00	285	C	0.6870	-99.00	11000	1	1
AAR0003744	12/29/1972	IL	2	40	-99	1948	115	-98	0.3750	-99.0000	-99.00	-99	-99	0.5000	-99.00	10148	1	1
AAR0001976	04/13/1970	SK	2	40	0	1930	115	-98	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	6000	1	0
AAR0003761	01/05/1973	PA	2	40	0	1963	212	B	0.4370	0.4370	78.00	212	B	0.4370	78.00	8000	1	0
AAR0003971	03/07/1973	PA	2	40	0	1945	115	-98	0.5000	0.5000	-99.00	115	-98	0.5000	-99.00	10027	1	1
AF63641	05/26/1979	IL	2	40	4	1954	285	C	0.6870	-97.0000	-97.00	-97	-97	0.6870	-97.00	11000	1	0
AAR0010907	06/01/1983	MB	2	40	4	1953	285	C	0.4370	0.4370	86.50	285	C	0.5000	86.50	10128	1	0
AAR0000861	04/09/1968	NY	2	40	4	-99	115	-98	0.3750	-97.0000	-97.00	-97	-97	0.5000	-97.00	8000	1	0
0920003K84	11/21/1984	IN	2	40	5	1964	212	B	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	1	0
AF60039	04/28/1977	IL	2	40	10	1965	212	B	-99.0000	-99.0000	-97.00	-97	-97	-99.0000	-97.00	20000	1	0
17036	03/18/1976	IL	2	40	12	1956	285	C	0.6870	-97.0000	-97.00	-97	-97	0.6870	-97.00	11000	1	0
AAR0003144	03/11/1972	IL	2	40	15	1948	212	B	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	8000	1	0
PA6	01/02/1976	WA	2	40	0	-99	-99	-99	-99.0000	-99.0000	-97.00	-99	-99	-99.0000	-97.00	12000	-99	0
D4107	11/04/1979	AL	2	41	0	1979	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	14000	2	0
D4107	11/04/1979	AL	2	41	0	1979	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	14000	2	0
AAR0008811	03/13/1980	ID	2	41	2	1973	128	B	0.7500	0.7500	-97.00	128	B	0.7500	-97.00	34000	2	0
AAR0008000	04/12/1982	AB	2	41	2	1981	128	B	0.5620	0.5620	114.87	128	B	0.5620	114.87	34048	2	0
AAR0010890	05/03/1983	MB	2	41	3	1980	515	7	0.4370	0.4370	110.81	515	7	0.4690	105.00	24000	2	0
AVA0095	03/26/1984	VA	2	41	7	1974	515	7	0.4370	0.4370	90.00	515	7	0.4370	90.00	12900	2	1
79049	10/12/1979	AB	2	41	-99	1965	212	B	0.4370	0.4370	103.00	212	B	0.4370	103.00	20871	1	0
AAR0007415	06/01/1985	SK	2	42	-99	1967	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	21000	2	0
JAN21982	01/14/1982	TX	2	42	1	1980	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	23528	2	0
080919	01/06/1994	NC	2	42	2	1984	515	7	0.4370	0.4370	100.62	515	7	0.4690	100.62	13467	2	0
0478OR203A	04/07/1978	OR	2	42	3	1974	515	7	0.4370	0.4370	101.00	515	7	0.4690	101.00	14802	2	1
TU0326	12/12/1994	OK	2	42	4	1990	516	7	0.4530	0.4530	110.25	516	7	0.4430	110.25	23589	2	0
AAR0009206	05/01/1987	MB	2	42	5	1965	212	B	-99.0000	-99.0000	118.75	212	B	-99.0000	104.25	32050	2	0
890314	03/22/1989	IL	2	42	5	1989	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	23000	2	0
D1617	03/10/1990	MI	2	42	5	1969	515	7	0.4370	0.4370	108.31	515	7	0.5000	102.00	17000	2	0
D79015	03/20/1979	IL	2	42	1	1975	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	20000	1	0
17339	10/19/1976	IL	2	43	4	1974	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	20598	2	0
010381A	03/25/1981	IN	2	43	4	1973	515	7	0.5000	-97.0000	-97.00	-97	-97	0.5000	-97.00	18000	2	0
GT2119	12/26/1991	IA	2	43	5	1991	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	17600	2	0
GT2119	12/26/1991	IA	2	43	5	1984	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	17600	2	0
B810001L82	12/05/1982	OH	2	43	15	1964	212	B	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	10000	2	0
310183103	01/25/1983	CA	2	44	0	1973	516	7	0.5620	-97.0000	-97.00	-97	-97	0.5620	-97.00	14000	2	0
T211186001	11/02/1986	MO	2	44	0	1965	212	B	0.4370	0.4370	118.19	212	B	0.4370	105.69	29321	2	0
529254	11/28/1999	LA	2	44	2	1996	516	7	0.4370	0.4370	110.25	516	7	0.4690	110.25	25785	2	0
80082	03/04/1980	AR	2	44	3	1976	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	22000	2	0
093468	02/15/1998	VA	2	44	3	1976	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	17538	2	0
093468	02/15/1998	VA	2	44	3	1975	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	17560	2	0
ME123	03/27/1968	TN	2	44	4	1984	515	7	0.4370	0.4370	99.00	515	7	0.4370	99.00	15000	2	0
16895	12/20/1975	LA	2	44	5	1974	515	7	0.4370	0.4370	103.25	515	7	0.4370	103.25	16170	2	0
70001E92	05/21/1992	NY	2	45	-99	1980	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	23532	2	0
0390FW238	03/27/1990	TX	2	45	0	1984	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	21000	2	0
0390FW238	03/27/1990	TX	2	45	0	1987	515	7	0.4370	0.4370	110.25	515	7	0.4370	110.25	18000	2	0
800076	04/03/1980	MA	2	45	0	1971	515	7	0.4370	0.4370	96.00	515	7	0.4370	96.00	13600	2	1
83220A	12/14/1983	TX	2	45	0	1972	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	26000	2	0
83220A	12/14/1983	TX	2	45	0	1972	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	26000	2	0
1186KA202	11/10/1986	MO	2	45	0	1980	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	24000	2	0
0530002C90	03/10/1990	PA	2	45	0	1988	128	BN	0.5620	0.5620	119.00	128	BN	0.5620	119.00	26000	2	0
0530002C90	03/10/1990	PA	2	45	0	1973	128	B	0.6250	0.6250	119.00	128	B	0.6870	110.00	26000	2	0
0530002C90	03/10/1990	PA	2	45	0	1971	128	B	0.6250	0.6250	119.00	128	B	0.6870	119.00	26000	2	0

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)

-99 = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
449205	03/16/1994	LA	2	45	0	1971	285	C	0.4370	0.4370	89.00	285	C	0.4690	89.00	8000	2	0
10002E94B	05/03/1994	NJ	2	45	0	1981	128	B	0.7080	0.7080	114.58	128	B	0.7080	114.58	33500	2	0
2021200001	12/05/1976	FL	2	45	2	1973	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	21000	2	0
2021200001	12/05/1976	FL	2	45	2	1973	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	24000	2	0
D1233	02/21/1979	NC	2	45	2	1971	515	7	0.4370	0.4370	102.50	515	7	0.5000	102.00	16000	2	0
1186OR204	11/22/1986	OR	2	45	2	1975	516	7	0.4490	0.4490	113.00	516	7	0.5000	113.00	29694	2	1
0889PC207	08/17/1989	ID	2	45	2	1981	515	7	0.4370	0.4370	98.62	515	7	0.4370	94.50	14000	2	0
20738	03/31/1995	MS	2	45	2	1988	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	29947	2	0
47806612	04/15/1978	GA	2	45	3	1966	515	7	0.4370	0.4370	99.12	515	7	0.4370	99.12	13279	2	0
84036	03/05/1984	MO	2	45	3	1965	212	B	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	15000	2	0
20057	12/15/1984	KY	2	45	3	1973	128	B	0.6250	0.6250	119.00	128	B	0.6870	119.00	26000	2	0
1292LU030	12/27/1992	LA	2	45	3	1977	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	17568	2	0
AAR0010491	11/02/1976	ON	2	45	4	1969	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	16000	2	0
10002	03/02/1976	IL	2	45	5	1975	515	7	0.4370	0.4370	101.00	515	7	0.4690	101.00	14000	2	0
10002	03/02/1976	IL	2	45	5	1969	515	7	0.4370	0.4370	105.12	515	7	0.5000	105.12	14210	2	1
TA8A7923	11/22/1979	MO	2	45	5	1967	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	21000	2	0
0110001D81	04/07/1981	NJ	2	45	5	1974	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	23388	2	0
19760A	02/03/1982	LA	2	45	5	1977	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	20000	2	0
PA984	11/16/1982	WA	2	45	5	1980	128	B	0.5620	0.5620	112.87	128	B	0.5620	112.87	25100	2	1
AAR0014573	01/31/1998	CA	2	45	5	1967	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33584	2	0
AF4491	04/22/1987	IL	2	45	6	1971	515	7	0.4370	0.4370	102.00	515	7	0.4370	102.00	16315	2	0
236	04/17/1978	NC	2	45	8	1972	515	7	0.4370	0.4370	108.00	515	7	0.5000	108.00	20665	2	1
236	04/17/1978	NC	2	45	8	1964	212	B	0.4370	0.4370	104.00	212	B	0.4370	104.00	20000	2	0
A110006J80	10/27/1980	NJ	2	45	10	1979	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	16000	2	0
83220B	12/14/1983	TX	2	45	10	1980	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	23000	2	0
AF5075	04/10/1988	IL	2	45	10	1974	537	A	1.1250	1.1250	94.50	537	A	1.1250	94.50	22000	2	0
AAR0013589	03/14/1994	MB	2	45	10	1984	515	7	0.4370	0.4370	102.00	515	7	0.4370	96.00	14100	2	0
039401019	03/01/1994	GA	2	45	10	1993	516	7	0.4370	0.4370	99.00	516	7	0.4370	99.00	13818	2	0
T25A15	03/26/1975	OK	2	45	15	1966	212	B	0.4370	0.4370	102.00	212	B	0.4370	102.00	20465	2	0
T25A15	03/26/1975	OK	2	45	15	1974	515	7	0.4370	0.4370	-99.00	515	7	0.4370	-99.00	24000	2	0
93-1060-25	09/14/1993	MB	2	45	20	1980	128	B	0.6030	0.6030	114.79	128	B	0.6030	114.79	34000	2	0
B0551	05/22/1981	CA	2	45	55	1966	515	7	-99.0000	-99.0000	-97.00	-97	-97	99.0000	-97.00	23000	2	1
B0551	05/22/1981	CA	2	45	55	1967	285	C	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	30000	2	0
B0551	05/22/1981	CA	2	45	55	1969	128	B	0.7750	-99.0000	-99.00	128	B	0.8120	-99.00	17378	2	1
B0551	05/22/1981	CA	2	45	55	1971	515	7	0.4370	0.4370	109.00	515	7	0.5000	108.00	23755	2	0
B0551	05/22/1981	CA	2	45	55	1965	285	C	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	16000	2	0
B0551	05/22/1981	CA	2	45	55	1960	285	C	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	10000	2	0
BOAWN0290	03/19/1986	OH	2	45	0	1964	212	B	0.4370	0.4370	104.00	212	B	0.4370	104.00	20000	1	0
0530002C90	03/10/1990	PA	2	45	0	1977	128	B	1.0000	1.0000	-99.00	516	7	1.2500	-99.00	20000	1	0
AWM519	03/20/1977	PA	2	45	2	1960	212	B	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	20000	1	0
T120284003	02/18/1984	OH	2	45	3	1966	212	B	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	11000	1	0
0110001D81	04/07/1981	NJ	2	45	5	1956	115	-98	0.6870	-97.0000	-97.00	-97	-97	0.6870	-97.00	11000	1	0
B0551	05/22/1981	CA	2	45	55	1955	285	C	0.6870	-97.0000	-97.00	-97	-97	0.6870	-97.00	11000	1	0
338552	03/28/1984	LA	2	46	2	1980	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4370	-97.00	24000	2	0
AAR0013593	04/01/1994	AB	2	46	5	1982	516	7	0.4370	0.4370	100.62	516	7	0.4690	100.62	13470	2	0
AAR0013593	04/01/1994	AB	2	46	5	1982	516	7	0.4370	0.4370	100.62	516	7	0.4690	100.62	13470	2	0
0420016C78	03/22/1978	NY	2	46	6	1963	285	C	0.4370	0.4370	-99.00	285	C	0.4370	-99.00	18000	2	0
AWN1039A	11/19/1981	OH	2	46	15	1971	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	21000	2	0
AAR0012890	12/18/1991	BC	2	46	-99	1989	209	L	0.5000	0.5000	102.00	209	L	0.5000	102.00	20513	1	0
AAR0014036	11/14/1995	BC	2	47	-99	1983	128	B	0.4370	0.4370	112.00	128	B	0.4370	106.00	21325	2	0
AAR0014036	11/14/1995	BC	2	47	-99	1983	128	B	0.4370	0.4370	112.00	128	B	0.4370	106.00	21325	2	0
AAR0014036	11/14/1995	BC	2	47	-99	1983	128	B	0.4370	0.4370	112.00	128	B	0.4370	106.00	21325	2	0
1194CB043	11/23/1994	IA	2	47	4	1981	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	20408	2	0
Y1348	12/16/1976	GA	2	47	7	1967	128	B	0.6870	0.6870	117.92	128	B	0.6870	117.92	33580	2	0
AAR0010963	09/11/1983	BC	2	48	-99	1969	128	B	0.6250	0.6250	118.05	128	B	0.6250	118.05	33800	2	0
AAR0011580	10/29/1988	BC	2	48	-99	1984	516	7	0.4440	0.4440	112.00	516	7	0.4370	112.00	25000	2	0
AAR0001441	04/24/1969	IL	2	48	0	1968	515	7	0.4370	0.4370	102.00	515	7	0.5000	102.00	10000	2	0
Y2322	03/04/1977	NC	2	48	0	1970	515	7	0.4370	0.4370	105.12	515	7	0.4690	105.12	10242	2	0
G82040301B	04/03/1982	ME	2	48	0	1981	515	7	0.4370	0.4370	100.62	515	7	0.4690	100.62	14000	2	0

Coding Legend:

- **INC** = Incident Number
- **DOA** = Date of Accident
- **SOP** = State or Province
- **TTA** = Type of Track and Accident (2 = Yard Collision)
- **TMP** = Temperature (degrees F)
- **TSP** = Speed (miles per hour)
- **YCB** = Year Car Built
- **SMS** = Tank Shell Material Specification
- **SMG** = Tank Shell Material Grade
- **STS** = Tank Shell Material Thickness, Small (inches)
- **STL** = Tank Shell Material Thickness, Large (inches)
- **SID** = Tank Shell Inside Diameter (inches)
- **HMS** = Tank Head Material Specification
- **HMG** = Tank Head Material Grade
- **HMT** = Tank Head Material Thickness (inches)
- **HID** = Tank Head Inside Diameter (inches)
- **CTC** = Car Tank Capacity (US gallons)
- **CST** = Car Sill Type (1=continuous, 2=stub sill)
- **LDL** = Lading Lost (0=none, 1=loss)

-99 = Unknown

INC	DOA	SOP	TTA	TMP	TSP	YCB	SMS	SMG	STS	STL	SID	HMS	HMG	HMT	HID	CTC	CST	LDL
1090HO203	10/26/1990	TX	2	48	0	1990	516	7N	0.4370	0.4370	110.25	516	7N	0.4370	110.25	20413	2	0
1090HO203	10/26/1990	TX	2	48	0	1988	516	7	0.4370	0.4370	110.25	516	7	0.4370	110.25	26529	2	0
SA104	10/10/1986	WI	2	48	1	1962	212	B	0.8250	0.9370	118.12	212	B	0.7440	104.00	32000	2	0
52510	02/07/1980	CA	2	48	3	1970	128	B	0.7790	-97.0000	-97.00	-97	-97	0.8120	-97.00	17000	2	0
46084	03/17/1977	VA	2	48	4	1971	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	18542	2	1
821024	10/29/1982	WI	2	48	4	1980	515	7	0.4370	0.4370	110.25	515	7	0.4690	110.25	24000	2	0
AX1375	12/23/1978	TX	2	48	5	1964	212	B	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	8000	2	0
310381102	03/15/1981	CA	2	48	5	1973	515	7	0.4370	0.4370	118.62	515	7	0.4370	115.12	30113	2	0
19302	03/16/1980	IL	2	48	7	1963	212	B	0.8120	0.9540	120.94	212	B	0.7500	102.37	31251	2	0
AF4763	10/12/1987	IL	2	48	10	1970	515	7	0.4370	0.4370	110.25	515	7	0.4370	106.00	21000	2	0
AAR0004592	10/19/1973	IL	2	48	20	1971	515	7	0.4370	-97.0000	-97.00	-97	-97	0.5000	-97.00	20000	2	0
AAR0001110	10/16/1968	NE	2	48	-99	1945	285	C	0.6870	0.6870	89.25	285	C	0.6870	89.00	10704	1	1
46084	03/17/1977	VA	2	48	4	1962	-99	-99	-99.0000	-99.0000	-99.00	-99	-99	-99.0000	-97.00	11000	1	0
107917096	10/28/1979	TN	2	48	5	1963	209	L	-99.0000	-99.0000	87.00	209	L	-99.0000	87.00	10088	1	0
091263	04/29/1997	IL	2	49	0	1969	128	B	0.6250	0.6250	118.05	128	B	0.6870	118.05	33800	2	0
C1924	10/25/1994	OR	2	49	1	1979	285	C	0.6250	0.6250	100.62	285	C	0.5620	100.62	13748	2	0
YN1092	10/06/1979	ND	2	49	2	1974	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	23000	2	0
SA121	11/25/1986	IA	2	49	4	1980	515	7	0.4370	0.4370	108.00	515	7	0.4370	108.00	21000	2	0
310180102	01/11/1980	CA	2	49	5	1973	515	7	0.4370	-97.0000	-97.00	-97	-97	0.4690	-97.00	23000	2	0
AAR0003040	01/22/1972	IL	2	49	15	1962	212	B	0.9370	0.9370	118.12	212	B	0.8120	102.37	30800	2	0
AAR0003040	01/22/1972	IL	2	49	15	1962	212	B	0.8120	0.8120	118.12	212	B	0.8120	102.37	31000	2	0
AAR0003040	01/22/1972	IL	2	49	15	1961	212	B	0.7810	0.7810	97.37	212	B	0.7810	97.37	30149	2	0
AAR0003040	01/22/1972	IL	2	49	15	1962	212	B	0.7810	0.7810	97.37	212	B	0.7810	97.37	30150	2	1

Coding Legend:

INC = Incident Number
DOA = Date of Accident
SOP = State or Province
TTA = Type of Track and Accident (2 = Yard Collision)
TMP = Temperature (degrees F)
TSP = Speed (miles per hour)

YCB = Year Car Built
SMS = Tank Shell Material Specification
SMG = Tank Shell Material Grade
STS = Tank Shell Material Thickness, Small (inches)
STL = Tank Shell Material Thickness, Large (inches)
SID = Tank Shell Inside Diameter (inches)
HMS = Tank Head Material Specification
HMG = Tank Head Material Grade
HMT = Tank Head Material Thickness (inches)
HID = Tank Head inside Diameter (inches)
CTC = Car Tank Capacity (US gallons)
CST = Car Sill Type (1=continuous, 2=stub sill)
LDL = Lading Lost (0=none, 1=loss)

-99 = Unknown

APPENDIX B

APPENDIX B

Summary of Canadian Tank Car Accidents

Canadian Accident History
and Damage Profile
(Subset of tank car coupling events at low temperature)

Table B-1: All Canadian Tank Car Accidents

RECORD ID #	FILE ID #	INCIDENT DATE	LOCATION	DAMAGE PROFILE SUMMARY	LAB REPORT	EQUIPMENT REPORTING MARKS	APPROX TEMP	REPORT AVAILABLE	RECOMMENDATIONS & CONCLUSIONS	DATE BUILT	MATERIAL, SPEC, BUILDER	OTHER COMMENTS
1	27 229/NTA	01-12-1989	Senneterre CN Rail	Head fracture above stub sill suspect hard impact	Part of Report	PROX 47921	-35 °C	YES	Yes. Discussions with the FRA/AAR - Welding Standards	Jan. 1970	Material ASTM A-285 grade C steel Builder: Procor, Oakville, Ontario. Spec CTC111 A60 W1	
2	55 229/NTA	09-02-1990	Winnipeg CP Rail	Crack in tank shell leak. Brittle fracture suspect high speed loading	Part of report	CGTX 29423	-8 °C	YES	Yes. Head support inspection. Welding standards. coupling speed			
3	125	30-4-92	Montreal CN Taschereau yard	Hump Yard Operator error with 20 mph impact	No	PROX 60066	Not available in record but not relevant to this failure	YES R92D0065	Hump yard operator error. While generating new hump list, operator signalled to system that hump was finished and so couldn't operate retarders. Car impacted at 20 mph into 33 stationary cars on track MC-31. Impact pushed in stub sill causing longitudinal fracture on underside of tank shell, releasing 2,360 gallons of sulphuric acid (H_2SO_4).		DOT/CTC 111A Material - carbon steel	
4	135	01/10/1993	Calgary	Routine inspection discovered 2 cracks in tank shell. Subsequent metallurgical tests concluded that cracks were from a heavy impact	No	BN 875146	Not available in record	Assessment only	None			
5	139	28/1/94	Brantford, Ontario	Inspection discovered stub sill crack down both sides of car	No	PROX 81631	Cold	Info Letter	None			
6	131	Aug-1993 Safety Advisory	Nanticoke, Ontario CN Rail	Cracked stub sill found by CN. TSB suspect impact contributed to failure	No	CITX 35805	Warm	No Report	None			
7	142	26/5/94	Moncton, New Brunswick CN Rail	Hump operator error resulted in tank car being impacted by a gondola car	No	ACFX 19367	?	No	None			
8	169	27/1/94	Montreal, Taschereau yard CN Rail	Tank shell fracture as a result of high impact forces	Yes x2 (Sims, and CANAC) and TSB lab report LP46/94	PROX 47917	-30 °C	Yes. TSB report R94D0033	Yes. Stub sill cracking susceptibility under impact conditions and cold temperature. This was incident that initiated the R & D into examining impact stresses on stub sill tank cars	Jan. 1969	Material ASTM A-285 grade C steel Impact energy at -30 °C = 5 ft. lbs compared with 62 ft. lbs at +22 °C. Builder: Procor, Oakville, Ontario. Spec CTC111 A60 W1	Car was humped empty in Taschereau yard during early morning hour of Jan. 26 and coupled at 2.8 mph. It was squeeze impacted by the next multiple hammer set of tank cars to couple. It was then moved to Montreal east end refinery and filled with gasoline. Car was then switched to CN Rivieres Des Prairie yard for train make up. Switch crew found car leaking, lost a few hundred gallons of gasoline on the track under stationary car.
9		4-2/94	Sarnia, CN Rail	Brittle fracture similar to #8 (PROX 47917	?	PROX 24017	0 °C	Yes. TSB lab report LP46/94				

RECORD ID #	FILE ID #	INCIDENT DATE	LOCATION	DAMAGE PROFILE SUMMARY	LAB REPORT	EQUIPMENT REPORTING MARKS	APPROX TEMP	REPORT AVAILABLE	RECOMMENDATIONS & CONCLUSIONS	DATE BUILT	MATERIAL, SPEC, BUILDER	OTHER COMMENTS
10	182	24/11/97	Carrier Quebec Mi. 10 Diamond sub CN Rail	Class 111A tank car split open circumferentially around tank center due to gap in reinforcing plate to washout securement and weld detail, in variance with design requirements. Fracture occurred under normal service loading at pre-existing crack.	Yes. TSB lab report LP186/97	UTLX 15076	-14 °C	Yes. TSB report R97D0253	Findings and TC subsequent Safety Action taken. No recommendations. During periodic qualification of tank cars in their fleets, the Union Tank Car Company and Procor now require a focused visual inspection in areas of transverse welds at bottom reinforcing plates.	Mar. 1984	Material ASTM A-285 grade C steel, impact energy = 5.2 ft. lbs at -10 °C. Builder: Riley-Beard, Shreveport, Louisiana. Specification DOT111 A100 W2	Copy of lab report on file. Large circumferential direction pre-crack 8 1/4" x 0.37" deep on tank bottom center area. Transverse (circumferential direction) welds on tank bottom joining the reinforcement plate and sump casting plate.
11	5 (Red tag)	10/01/1982	Manitoba	Suspect impact and shell dent may have contributed to brittle fracture and tank failure with propane. Train derailment and propane fire.	No	CGTX63712	-37 °C	Yes. 226	12 Recommendations including (xii) "That material specs of AAR M-1002 be amended requiring mandatory use of steels, on all newly built cars, with NDT temperatures below those expected in Canadian winter service.		Material ASTM A-441 (AAR M128-A).	
12	12 (Red tag)	28/2/84	Toronto, CN Rail Macmillan Yard	Humped 112340W tank with butane residue and natural gas vapours at approximately 100 psig. This resulted in stresses which brought a pre-existing crack to failure and the tank head separated from the shell. This empty car was humped normally into track, but was overtaken by a second faster moving loaded car marshalled into the same track. They impacted, increasing the speed of the empty tank, and fracturing the tank header along the pre-existing crack. The internal residue pressure blew the tank header off the car and it landed several tracks away. The butane load was purged with natural gas at about 100 psig to unload the butane. The tank pressure should have been reduced to 50 psig or so after unloading, but this procedure was not done. Empty cars containing flammable vapours are shipped under modest pressure to prevent any air (oxygen) ingression to lower risk of explosion and fire.	Findings, summary only.		-10 °C	Yes, judicial inquiry report	Speed restrictions on humping dangerous goods cars & hump yard operator training.	Nov. 28,1980	Material TC-128B steel. Builder: Procor, Oakville, Ontario. (Procor was a wholly owned subsidiary of Union Tank Car Company). Spec CTC112J 340 W.	Failed at a pre-existing welding crack 2 feet long, hydrogen assisted through 40% of tank wall thickness. Wall thickness was 0.7 inches. Tank header material should have been normalized, but grain size was ASTM2 or 3 (Should have been 7), due to excessively high head forming temperature used by subcontractor supplying formed tank heads.
13	21 (Red Tag)	04/01/1986	Campbellton yard, Campbellton, New Brunswick CN Rail	Brittle fracture of shell caused failure. At least one strong impact in car history.	Lab data included in report	NATX 13657	-14 °C	Yes. 226	Limitations on use of ASTM A-515 steel, increased shop monitoring, same design dye penetrant testing annually.		Material ASTM A-515 grade 70 steel 7/16 inch thick. Builder: Richmond Tank Car and manufacturing Company. Spec DOT111 A100 W2.	Car repair weld made in a "required weld free" area by North American Car Corporation in July 30, 1982 was point of origin of failure. The inserted plate repair was poorer material than the parent material. Car draft gear was a Cardwell-Westinghouse Mark 50 draft gear which had one coil broken on main return spring.

Canadian Accident History
and Damage Profile
(Subset of tank car coupling events at low temperature)

RECORD ID #	FILE ID #	INCIDENT DATE	LOCATION	DAMAGE PROFILE SUMMARY	LAB REPORT	EQUIPMENT REPORTING MARKS	APPROX TEMP	REPORT AVAILABLE	RECOMMENDATIONS & CONCLUSIONS	DATE BUILT	MATERIAL, SPEC, BUILDER	OTHER COMMENTS
14	-	February, March, and April 1986	Various	Weld shear influenced by impact	Lab data included in report	UTLX 81555	?	Yes, 226	Lab conclusions only			
15	-	Feb. 3, 1997	Thornton Yard, Vancouver B.C. CN Rail	20" shell crack, stiffener	Yes, LP50/97 Rocheleau	GATX 13833	?	Yes, TSB R94V0108, R93E0052		01/01/1974	Specification DOT111 A100 W5	Spilled hydrochloric acid. Sent to CXY North Vancouver. Associated with GATX 43924 (TSB report R96C0126 & R93E0049)
16	-	Feb. 7 1997	Alyth Yard, Calgary, Alberta CP Rail	4 inch crack in shell end of stub sill	?	NATX 25346	?	Yes, TSB R97C0038			DOT111 A100 W1	Kerosene service. Sent to PDS in Calgary for repairs.
17	-	Mar. 4, 1997	Macmillan yard, Toronto, Ontario. CN Rail	Cracked stub sill at base of head brace		PROX 47704	?	None in TSIS			CTC111 A100 W1	Methyl alcohol service. Thought to have been involved in another accident (possibly PROX 47704) in Calder yard (CN Rail), Edmonton, Alberta
18	-	Mar. 12 1997	Calgary, Alberta. PDS shop	41 inch crack in head stub sill weld. No head brace		DCTX 33197	?	Yes, TSB R94T0228			DOT111 J340 W	LPG service. Husky, Elspeth detected crack at loading rack. Car sent to PDS for repairs. PDS received no direction on what to do with any parts for TC or TSB.
19	-	Mar/April 1996	Calgary, Alberta. PDS shop	Complete head failure	Yes. TSB lab LP 21/96	PLMX 34355	?	Yes. TSB lab report LP21/96. None in TSIS			DOT112 J340 W	LPG service. New head applied by PDS after accident on BC Rail in Prince George, British Columbia in 1996. During hydrostatic test, at approximately 325 psig, tank head blew off. Head supplied by Trinity Industries in Dallas Texas.

Canadian Accident History
and Damage Profile
(Subset of tank car coupling events at low temperature)

RECORD ID #	FILE ID #	INCIDENT DATE	LOCATION	DAMAGE PROFILE SUMMARY	LAB REPORT	EQUIPMENT REPORTING MARKS	APPROX TEMP	REPORT AVAILABLE	RECOMMENDATIONS & CONCLUSIONS	DATE BUILT	MATERIAL, SPEC, BUILDER	OTHER COMMENTS
20	-	Jan. 30, 1994	Westree, Ontario Mi 56.7 Ruel Sub CN Rail	Train derailment due to a broken rail. Two 111A tank cars released 79,000 kg of Vinyl acetate and one 111A car carrying methanol was leaking.	Yes, TSB lab LP 17/94	Cars nos not given in report. Derailment caused by a broken rail	-45 °C	Yes, TSB R94T0029			111A cars.	A methanol 111A car and a Propane 112J car were damaged but did not lose product in the train derailment at 46 mph.
21	-	Jan. 21, 1995	Gouin, Quebec Mi 82.2 La Tuque sub. CN Rail	Train derailment due to loss of track gauge. 11 sulphuric acid cars of 28 derailed, releasing 51,000 gallons of sulphuric acid. All were 111A spec cars.	Yes, TSB lab LP13/95	Car nos. not given. Derailment caused by a track failure.	-5 °C	Yes, TSB R95D0016			111A cars.	Eleven 111A sulphuric acid cars leaked 51,000 gallons of product due to a train derailment.
22	-	Mar. 31 1995	Toronto, Ontario Macmillan Yard CN Rail	A shallow crack had developed in the weld joining the brake cylinder mounting pad to the bottom of the tank. It was determined that the weld was of inferior quality. The crack slowly progressed over time until it eventually penetrated the bottom of the tank, allowing 23 litres of toluene to escape at the rate of 5 drops/minute.	Yes, TSB lab LP 61/95	CGTX 20922	Not given in report. Leak found at 1.15 am on a Toronto winter morning.	Yes, TSB R95T0092	Rail Safety Advisory to Transport Canada (TC) alerting them to the issue of cracks in the welds joining brake cylinder mounting pads to the bottom of tank cars.	1970	Material ASTM A-285 grade C steel. Builder: Hawker Siddeley Canada Inc. [Trenton Works Ltd], Trenton, Nova Scotia. Spec DOT111 A1000 W1	The leak was the result of a fatigue crack that developed at the toe of the circumferential weld joining a tubular support pad to the tank and propagated through the tank wall.
23	-	Oct. 17, 1994	Lethbridge, Alberta Mi 108.05 Taber sub. CP Rail	Train derailment at 29.6 mph due to rail fracture due to worn and fatigue cracked rail. 4 tank cars leaked 56,000 litres of Methanol. All were 111A cars.	No	Car numbers PROX 40655 PROX 40737 ACFX 87276 ACFX 89851	2 °C	Sixteen of the derailed cars were tank cars loaded with various dangerous goods. About 455 litres of gasoline was released from one tank car and a small quantity of butane was released to the atmosphere from two leaking pressure tank cars.	Amendment Schedule No. 21 to the Transportation of Dangerous Goods Regulations makes mandatory the use of tank car standard CAN/CGSB-43.147-94. This standard restricts the use of 111A tank cars, and removes over 80 dangerous goods previously authorized for transportation in Class 111A cars.	?		
24	-	11-Mar-96	River Glade, New Brunswick Mi 6.44 Sussex Sub. Cn Rail	Train derailment account a broken rail during a train initated emergency brake application. Sixteen of the derailed cars were tank cars loaded with various dangerous goods. Approximately 455 litres of gasoline was released from one tank car and a small quantity of butane was released to the atmosphere from two leaking pressure tank cars.	No	CGTX 30413 DCTX 34255 CGTX 63723	-8 °C	Yes, TSB R96M0011	CGTx has undertaken to inspect all sister cars and verify the integrity of the eduction pipes and guide brackets, ensuring that their alignment meets current norms. Additional measures in accordance with AAR M-1002 Appendix R will be taken to reduce the possibility of excessive stresses being generated at the welds connecting the guide brackets to the tank.	1965	CGTx 63723 Builder: GATX, Chicago. Original spec DOT112A340W, but later refitted to DOT112J340W. Material: AAR-M128 steel.	CGTX 30413 was loaded with gasoline and DCTX34255 held butane residue. Both leaking from punctures in side of tank. CGTX 63723 contained butane residue and was leaking slightly (discovered 3 days after derailment).

Canadian Accident History
and Damage Profile
(Subset of tank car coupling events at low temperature)

RECORD ID #	FILE ID #	INCIDENT DATE	LOCATION	DAMAGE PROFILE SUMMARY	LAB REPORT	EQUIPMENT REPORTING MARKS	APPROX TEMP	REPORT AVAILABLE	RECOMMENDATIONS & CONCLUSIONS	DATE BUILT	MATERIAL, SPEC, BUILDER	OTHER COMMENTS
25	-	Oct. 7, 1997	Chatham yard, Chatham, Ontario CSX/CP Rail Interchange tracks	A loaded pressure tank car containing 107,800 lbs of liquefied butane was discovered leaking from the B-end centre sill area. Frost was observed behind the bolster in the area where the jacket and stub sill meet at the tank car's B-end right side (BR location)	Yes, TSB lab report LP160/97	DCTX 33126	15-20 °C	Yes, TSB R97S0008	On 01 September 1998, amendment schedule No. 23 to the *Transportation of Dangerous Goods Regulations* came into force, replacing section 73.3 ("Qualification and Maintenance of Tank Car Tanks") by part 80 ("Continuing Qualification and Maintenance of Tank Cars"). As part of this change, section 73.31 was amended to remove the requirement for hydrostatic testing of fusion-welded tank cars. New inspection requirements have been introduced that are specifically designed to detect weld defects. Test methods to determine that the welds are in proper condition include dye penetration, radiology, magnetic particle, ultrasonic, and optically aided visual inspection. Hydrostatic testing is being phased out and is no longer authorized for non-insulated, non-jacketed tank cars. A similar change has been made to the Federal Railroad Administration (United States) requirements	1966	Owner: PLM Transportation Corporation of Chicago. Built by Davie Ship Building Ltd., Lauzon, Quebec to **CTC-114A specification** for anhydrous ammonia service. Converted to CTC-114S in April 1980 by Procor Ltd of Oakville, Ontario. Converted again in Sept. 1980 to **CTC-114J** by Procor Ltd. Modified to CTC-112J specification in Dec. 1991 by CGTX Inc, Moose Jaw, Saskatchewan for liquefied petroleum gas service, when a stub sill inspection required by TC was carried out. A crack was observed in the A-end sill cope, and the welds in the sill flange area were noted to be poor. The crack was repaired, and the car returned to service. In September 1996, Procor Ltd of Oakville repaired cracks in the centre sill plate area found during periodic valve testing and maintenance. The tank car was hydrostatically pressure-tested to 340 psi in 1991, over 10 years after the crack was produced. This test did not reveal the crack. It would seem that current visual inspection methods and pressure testing may not always ensure tank car integrity.	The nature of the crack indicates that it had existed in the form of a "closed through crack" for a considerable time. The existence of a through crack that does not leak, although rare, is a well-documented phenomenon. The physical evidence also indicates that the crack was a one-time event that was initiated at the 1980 installation of the protective jacket. Therefore, the crack was sufficiently tight so as not to leak during normal service loads for 17 years. Tank car DCTX 33126 had derailed in the CN Saint John Yard, New Brunswick, on 18 April 1997. It appears that, only after experiencing an extraordinary event such as the Saint John derailment, the crack opened to the extent where it could leak. It is probable that the buff and draft forces applied to the car at or near Chatham Yard on delivery were sufficient to prompt escape of the product.
26	-	Feb. 26, 1999	Neswabin, Ontario. Mi 255.1, Ruel sub. CN Rail	Train derailment at 42 mph derailed 20 cars including one tank car loaded with LPG and 2 tank cars loaded with benzene and dicyclopentadiene. One of the cars , AGEX 1001,with the benzene/ dicyclopentadiene mixture was punctured in the derailment, resulting in total loss of product. The derailment was caused by a burned off journal on car CN 604607	Yes, TSB lab report LP109/99	AGEX 1001	-10 °C	Yes, TSB report R99T0031	Subsequent to the accident, a large number of safety initiatives were undertaken by Canadian National (CN) to address the safety deficiencies identified in the areas of reference manuals, work procedures, job aids, and supervision relating to the activities of the rail traffic control mechanical service representatives (RTC Mechs) and hot box operators (HBOs).	?	?	

Canadian Accident History
and Damage Profile
(Subset of tank car coupling events at low temperature)

RECORD ID #	FILE ID #	INCIDENT DATE	LOCATION	DAMAGE PROFILE SUMMARY	LAB REPORT	EQUIPMENT REPORTING MARKS	APPROX TEMP	REPORT AVAILABLE	RECOMMENDATIONS & CONCLUSIONS	DATE BUILT	MATERIAL, SPEC, BUILDER	OTHER COMMENTS
27	-	Aug. 27,1999	Wesco spur, Cornwall, Ontario. Mi 69.4, Kingston sub. CN Rail	A CN crew was performing switching operations on the Wesco spur, when six tank cars ran away on track CB17. The cars rolled eastward for 475 feet and struck the stop block at the end of the track. At the time of impact, one car, STEX 20520, loaded with 146,660 lbs of Heptanol derailed and its tank was punctured. Approximately 5 000 gallons of this product, a class 3 combustible liquid, NA 1993, was released but was almost all recovered.	No	STEX 20520	26 °C	Yes. TSB report R99D0159	In September 1999, Canadian National (CN) issued new instructions for the Wesco spur in Cornwall. The instructions require that all rolling stock be grouped and secured with the appropriate number of hand brakes as required under special instructions to Rule 112. Also, cars must rest against the stop blocks on tracks so equipped. A full stop must be made 6 to 12 feet from any coupling. The same instructions apply to tracks with crescent stops, except that rolling stock must be left standing 6 to 12 feet from the crescent stop. In October 1999, CN implemented the above instructions on several spur tracks and industrial tracks in the Kingston Subdivision	?	?	Even though the tank cars in draft B struck the stop block at very low speed, the tank did not withstand the impact and it was punctured
28	-	Sept. 23, 1999	Britt, Ontario Mi 202.98 Bala sub. CN Rail	Train derailment at 35 mph caused by a torsionally rigid empty tank car in the entry spiral of curve with deficiencies in track geometry. The derailed equipment included 14 residue tank cars last containing liquefied petroleum gas (LPG), 1 tank car loaded with LPG and 3 tank cars loaded with anhydrous ammonia. The loaded LPG car and one of the loaded anhydrous ammonia cars were breached, each releasing product and igniting, causing several fires. PROX 81552, loaded with 127,560 lbs of LPG, exploded in a BLEVE 37 minutes after the derailment, with pieces of the tank shell and jacket projected in all directions. PROX 81879, loaded with 158,400 lbs of anhydrous ammonia, had a 6" x 4" hole in the tank shell, resulting in near complete loss of product.	Yes. TSB lab report LP 112/99	PROX 81879 PROX 81552	18.2 °C	Yes. TSB report R99T0256	To better understand the cumulative effect of combination track geometry defects, Canadian National (CN), Canadian Pacific Railway (CPR) and Transport Canada (TC) are currently collaborating on a joint research study targeted at characterizing the effect of combination geometry defects. TranSys Research Ltd., a transportation research and consulting group based in Kingston, Ontario, has been retained to provide technical expertise in conjunction with field-testing of instrumented rail cars. Measured car performance is being correlated with track geometry data to identify track locations that generate an inappropriate vehicle response for a specified car type.	Oct. 25,1968 and 1966	Builder : Procor Specification DOT 112A340W to carry LPG / anhydrous ammonia . The car was later converted and stencilled as a DOT 112J340W. Car PROX 81552 was manufactured in 1966 and converted from a DOT 112A400W to a DOT 112J400W in 1981. Both cars were thermally protected by applying a 0.65 inch-thick (16.5 mm) blanket of spun ceramic fibre (Fiberfrax) over the shell and heads and covering the shell and top half of the heads with a gauge 11 steel jacket which is approximately 0.125 inch (3 mm) thick. The head protection system fitted on both cars is a half head shield design, where only the lower half section (bottom) is made with thicker steel material. The material consists of a 0.5 inch-thick (13 mm) structural steel plate (American Society for Testing and Materials (ASTM) A36) that is shaped and fitted to cover the bottom half and the centre of the head.	

Canadian Accident History
and Damage Profile
(Subset of tank car coupling events at low temperature)

RECORD ID #	FILE ID #	INCIDENT DATE	LOCATION	DAMAGE PROFILE SUMMARY	LAB REPORT	EQUIPMENT REPORTING MARKS	APPROX TEMP	REPORT AVAILABLE	RECOMMENDATIONS & CONCLUSIONS	DATE BUILT	MATERIAL, SPEC, BUILDER	OTHER COMMENTS
29	-	Dec. 30,1999	Mont St. Hilaire, Quebec. Mi 50.84 St. Hyacinthe sub. CN Rail	Two opposing freight trains passing each other on double track collided and sideswiped each other. The westbound train derailed due to a broken rail weld, and derailed cars fouled the eastbound track in front of the westbound ULTRATRAIN® unit tank train, travelling at 53 mph. The eastbound freight train was limited to 50 mph at the time of collision. 35 tank cars derailed. 11 were carrying approximately 1 million litres of gasoline (UN 1203) and 24 contained approximately 2.3 million litres of heating oil (UN 1202). The two crew members on the eastbound freight train were fatally injured in the accident. Approximately 150 families living within a two-kilometre radius of the accident site had to be temporarily evacuated. Two locomotives and 61 cars were damaged in the accident. Approximately 2.7 million litres of hydrocarbons spilled and caught fire, damaging private property, public property and the environment.	No	GATX/CGTX ULTRATRAIN unit train tank cars	-11 °C	Yes, TSB report R99H0010	Many, but not related to tank car construction issues	1997	Specification 111A modified	The Ultratrain cars were designed by the General American Transportation Corporation (GATX) and its Canadian subsidiary, Canadian General Transportation Company (CGTX). The plans and specifications were based on the existing standards for Class 111A cars, with some modifications to meet the requirements of CN and Ultramar Canada Inc. The cars were permanently coupled in 17-car blocks, with piping and related equipment that allowed loading or unloading of the entire block from a single connection at one end. The cars did not have bottom outlets. To lessen the risk of accidental spills, the isolation valves were placed in a protective housing and had to be closed when the cars were moving, the flexible hoses linking the cars were designed to break if the cars separated, and the rigid elbows for the hoses were designed to fail before the connection for the isolation valves.
30	-	Mar. 14, 2000	Temagami, Ontario. Mi 63.4 Temagami sub. Ontario Northland Railway	A southward freight train, derailed 29 cars in a right hand curve at 39 mph at Mile 63.4 of the Temagami Subdivision, near Temagami, Ontario due to gauge widening on track structure unable to resist nominal lateral loads. Twenty-five derailed tank cars contained sulphuric acid. Approximately 386,000 litres of sulphuric acid was spilled. Approximately 242,000 litres of the product was absorbed by the surrounding ground and approximately 144,000 litres entered the Martin Creek waterway, 35,000 litres of which migrated to Hornet Lake. None of the spilled product was recovered in its natural state.	Yes, TSB lab report LP032/00	No car numbers given in report	1 °C	Yes, TSB report R00T0067	Recommendations related to giving better top valve protection for 111A cars in sulphuric acid service, and non tank car issues re track maintenance.		111A tank cars	
31	-	Jan. 27,1996	Prince George, B.C.	Tank car loaded with LPG was impacted by 3 locomotives	Yes	PLMX 34355	-26 °C	No		Oct. 1968	TC 128 Grade B steel Charpy test results: @-50°F, 3 ft. lbs.; @-31°F, Charpy impact energy was 3, 3, and 4 ft lbs.; @+5°F, Charpy impact energy was 6, 6,and 8 ft. lbs.; @41°F, Charpy impact energy was 18, 22, and 10 ft. lbs.	

APPENDIX C

Bibliography

Accidents

1. Eiber, R.J., Maxey, W.A., Duffy, A.R., "Analysis of Fracture Behavior of Tank Cars in Accidents," Report No. R-143 (RA-12-2-20), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, September 1972.

2. Phillips, E.A., Pellini, W.S., "Phase 03 Report on Behavior of Pressure Tank Car Steels in Accidents," Report No. RA-03-6-48 (AAR R-553), Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, June 1983.

3. Phillips, E.A., Role, H., "Analysis of Tank Cars Damaged in Accidents 1965 through 1986, Documentation Report," Report No. RA-02-6-55 (AAR R-709), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, January 1989.

4. Hazel, M.E., "Tank Car Accident Data Analysis," Report No. DOT/FRA/ORD-91/05, U.S. Department of Transportation, National Technical Information Service, Springfield, Virginia, June 1991.

5. Sidla, G., "Tank Car Stub Stills," Report No. LP 106/91, Transportation Safety Board of Canada, Engineering Branch Report, December 5, 1991.

6. Rocheleau, D.C., "Rail Tank Car Failure," Report No. LP 56/94, Transportation Safety Board of Canada, Engineering Branch Report, May 9, 1994.

7. Rocheleau, D.C., "Tank Car Wheel Gouge," Report No. LP 41/95, Transportation Safety Board of Canada, Engineering Branch Report, May 17, 1995.

8. Rocheleau, D.C., "Tank Car Head Plate Failure," Report No. LP 21/96, Transportation Safety Board of Canada, Engineering Branch Report, June 27, 1996.

9. Rocheleau, D.C., "Tank Car Failure," Report No. LP 51/96, Transportation Safety Board of Canada, Engineering Branch Report, August 9, 1996.

10. Mathieu, M.J., "Examination and Analysis of Fracture to Centre Bottom of Derailed Tank Car," Report No. LP 57/96, Transportation Safety Board of Canada, Engineering Branch Report, June 25, 1996.

11. Rocheleau, D.C., "Tank Car Plate Failure," Report No. LP 50/97, Transportation Safety Board of Canada, Engineering Branch Report, June 11, 1997.

12. Rocheleau, D.C., "Butane Tank Car Leak," Report No. LP 160/97, Transportation Safety Board of Canada, Engineering Branch Report, February 6, 1998.

13. Rocheleau, D.C., "Sulphuric Tank Car Mid-Span Fracture," Report No. LP 186/97, Transportation Safety Board of Canada, Engineering Branch Report, February 24, 1998.

14. Rocheleau, D.C., "Hydrochloric Tank Car Reinforcement Bar Crack," Report No. LP 20/98, Transportation Safety Board of Canada, Engineering Branch Report, April 14, 1998.

15. "Tank Car Failure with the Release and Ignition of Propane, Selkirk, New York, March 6, 1996," NTSB Report No. HZB-98-02, National Transportation Safety Board, Washington, D.C., April 20, 1998.

16. Hughes, J.P, Heuer, C.F., Anderson, T.L., "Fracture Behavior of Tank Car Steels in Accidents from 1981 through 1994," Sims Professional Engineers, AAR Report No. R-924 (Report No. RA-03-6-62), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR, Washington, D.C., December 1998.

Pellini/Fracture

1. Pellini, W.S., "Introduction to AAR Guidelines for Fracture-Safe Design Involving Temperature – Transition Sensitive Structural Steels," Report No. R-383, Project No. H-001, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, August 1979.

2. Pellini, W.S., "Manual of Engineering Procedures for Fracture-Safe Design," Report No. R-451, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, November 1980.

3. Pellini, W.S., "Guidelines for Fracture-Safe Design of Steel Structures," Report No. R-455, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, November 1980.

4. Pellini, W.S., "Slide Graph Fracture Analysis System," Report No. R-552, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, June 1983.

5. Pellini, W.S., "Guidelines for Fracture Mechanics Analysis of Pressure Tank Car Structural Integrity Factors," Report No. R-586, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, June 1985.

Pellini/Fatigue

1. Pellini, W.S., "Engineering Considerations in Design Against Fatigue Failure," Report No. R-306, Project No. H-301, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, March 1978.

2. Pellini, W.S., "Procedures for Analysis of Fatigue Damage Effects in Weld Defects," Report No. R-346, Project No. H-001, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, January 1979.

3. Pellini, W.S., "Introduction to ARR Guidelines for Establishing Defect-Quality Criteria in Fatigue Design," Report No. R-387, Project No. H-301, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, August 1979.

4. Pellini, W.S., "Guidelines for Fatigue-Reliable Design of Steel Structures," Report No. R-490, Association of American Railroads Research and Test Department, AAR Technical Center, Chicago, Illinois, September 1981.

Steels Evaluation

1. Pellini, W.S., Eiber, R.J., Olson, L.L., "Phase 03 Report On Fracture Properties of Tank Car Steels – Characterization and Analysis," Report No. RA-03-4-32 (AAR R-192), RPI-AAR Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, August 1975.

2. Eiber, R.J., Olson, L.L., "Final Phase 03 Report, Material Study on Steels Used in Current and Former Tank Car Construction and From Cars Involved in Accidents," Report No. RA-03-5-33 (AAR R-193), RPI-AAR Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, August 1975.

3. Pellini, W.S., "Feasibility Analysis for Tank Car Applications of New Microalloyed and Controlled Rolled Steels – Description of Fracture Properties and Comparisons with Steels in Present Use," Report No. R-543, Association of American Railroads, AAR Technical Center, Chicago, Illinois, April 1983.

4. Phillips, E.A., Eiber, R.J., Coughlin, S.A., Heideman, P.B., Fec, M.C., "Evaluation of New Steels for Tank Cars," Report No. RA-03-7-53 (AAR R-643), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, April 1987.

5. Phillips, E.A., Eiber, R.J., Stephens, D.R., Rosenfield, M.S., Ahlbeck, D.R., Rodabaugh, E.C., "Tank Car Design Basis – Yield vs. Tensile," Report No. RA-03-8-54 (AAR R-668), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, October 1987.

6. Phillips, E.A., "Evaluation of New Steels for Tank Cars, Phase II," Report No. RA-03-9-59 (AAR R-773), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR Technical Center, Chicago, Illinois, May 1991.

7. Hughes, J.P., Heuer, C.F., Anderson, T.L., "Fracture Behavior of Tank Car Steels in Accidents from 1981 through 1994," Sims Professional Engineers, AAR Report No. R-924 (Report No. RA-03-6-62), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR, Washington, D.C., December 1998.

8. Heuer, C.F., Warke, W.R., Anderson, T.L., "Metallurgy, Properties and Commercial Availability of Microalloyed Plate Steels," Sims Professional Engineers, AAR Report No. R-924 (Report No. RA-03-6-63), RPI-AAR Railroad Tank Car Safety Research and Test Project, AAR, Washington, D.C., March 1999.

9. Hicho, George E., Harne, Donald E., "Weld and Heat Affected Zone Crack Arrest Fracture Toughness of AAR TC128 Grade B Steel," NISTIR Report No. 4767

(No. 25), National Institute of Standards and Technology, Gaithersburg, MD, February 1992.

10. Hicho, George E., Harne, Donald E., "Mechanical Properties and Fracture Toughness of AAR TC128 Grade B Steel in the Normalized, and Normalized and Stress Relieved Conditions," NISTIR Report No. 4660 (No. 24), National Institute of Standards and Technology, Gaithersburg, MD, September 1991.

11. Hicho, George E., "Crack Arrest Fracture Toughness Measurements of Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel, and Micro-Alloyed, Control-Rolled, and Inclusion Shape Controlled A 8XX Grade B Steel," NISTIR Report No. 4501, (No. 21), National Institute of Standards and Technology, Gaithersburg, MD, February 1991.

12. Hicho, George E., Smith, John H., "Determination of the NDT Temperature and Charpy V-Notch Impact Properties of AAR TC128 Grade B Steel and A 8XX Grade B Steel," NISTIR Report No. 4300, (No. 20), National Institute of Standards and Technology, Gaithersburg, MD, April 1990.

13. Hicho, George E., Smith, John H., "Mechanical Properties and Fracture Toughness of AAR TC128 Grade B Steel and A Micro-Alloyed, Control-Rolled Steel, A 8XX Grade B, From -80°F to +73°F," NISTIR Report No. 90-4289, (No. 19), National Institute of Standards and Technology, Gaithersburg, MD, April 1990.

14. Hicho, George E., "The Mechanical, Stress-Rupture, and Fracture Toughness Properties of Normalized and Stress Relieved AAR TC128 Grade B Steel at Elevated Temperatures," NISTIR Report No. 5157, (No. 26), National Institute of Standards and Technology, Gaithersburg, MD, March 1993.

Couplers

1. Wisnowski, M.J., "Coupler Steel Study," Report No. R-107, Association of American Railroads, AAR Technical Center, Chicago, Illinois, December 1970.

2. Morella, N., Wallace, J., Maino, R., "Study of the Fatigue Life Characteristics of Cast Steels Used in the Railroad Industry," RPI-AAR Coupler Safety Project, AAR Technical Center, Chicago, Illinois, February 1978.

3. Pellini, W.S., Stone, D.H., "Analysis of Defects Associated With In-Service Fatigue Cracking of Coupler Components," Report No. R-351, Association of American Railroads, AAR Technical Center, Chicago, Illinois, November 1978.

4. Morella, N., Wallace, J., Canete Sigla, P., "Study of Fracture Toughness Characteristics of Cast Steels Used in the Railroad Industry (Study of AAR Grade B, C (N&T), C (Q&T) and E Steels.)," RPI-AAR Coupler Safety Project, AAR Technical Center, Chicago, Illinois, September 1979.

5. Lange, E.A., Fleming, L.D., Stone, D.H., "Fracture Properties of Couplers and Yokes," Report No. R-500, Association of American Railroads, AAR Technical Center, Chicago, Illinois, October 1981.

6. Fleming, L.D., "Impact Fracture Properties of Reconditioned Yokes and Couplers," Report No. R-548, Association of American Railroads, AAR Technical Center, Chicago, Illinois, April 1983.

General

1. Tetelman, A.S., Stone, D.H., "An Introduction to the Fracture Mechanics of Railroad Materials," Report No. R-157, Association of American Railroads, AAR Technical Center, Chicago, Illinois, May 1974.

2. NMAB Committee on Rapid Inexpensive Tests for Determining Fracture Toughness, "Rapid Inexpensive Tests for Determining Fracture Toughness," Report No. NMAB-328, National Materials Advisory Board, National Academy of Sciences, Department of Defense, Washington, D.C., 1976.

3. NMAB Committee on the Dynamic Response of Materials Subjected to High Strain Loading, "Response of Metals and Metallic Structures to Dynamic Loading," Report No. NMAB-341, National Materials Advisory Board, National Academy of Sciences, Washington, D.C., May 1978.

APPENDIX D

Brief Summary of Pellini's Fracture Analysis Methodology

Pellini's methodology for fracture-safe design uses fracture mechanics principles and a "master curve" approach to analyze tank car component failure at low temperatures [D1]. This approach is embodied in Figure D-1 which shows the fracture initiation curves for dynamic and slow loading rates as well as the crack arrest envelope for an arbitrarily selected nil ductility temperature (NDT) of 40°F. For a different NDT, it is only necessary to translate the curves parallel to the temperature axis until the index is opposite the NDT for the desired material. (While the crack arrest envelope is depicted for a 1 in. thick section, envelopes can be developed for other thicknesses.) The fracture initiation curves and the crack arrest envelope depend on material data for the plane-strain dynamic initiation fracture toughness K_{Id} as a function of temperature. Based on dynamic K_{Id} and crack arrest data developed for low to intermediate strength steels, a reference curve of K_{Id} as function of temperature relative to NDT was developed [D2] and is depicted in Figure D-2. This reference K_{Id}-curve enables the development of the curves in Figure D-1 for a surface crack as well as other cracked configurations. The distributions of NDT for generic classifications of steels developed by AAR are included in the lower portion of Figure D-1 [D2] so that it can be applied to typical tank car steels.

Figure D-1 can be used several ways. For a specified applied stress relative to the yield stress and a crack size, the figure can be used to determine the limiting operating temperature to preclude initiation of crack growth. Alternatively, for a given applied stress and operating temperature for the material, the critical crack size can be established from Figure D-1. This critical crack size can be used to set defect inspection requirements. The arrest envelope in Figure D-1 can also be used to determine the temperature for which arrest of a through thickness crack can be expected for a specified applied stress. Since the crack arrest temperature is in general greater than the limiting temperature for initiation of crack growth, the former provides a conservative estimate for the minimum operating temperature to avoid a catastrophic failure; i.e., a leak before a break.

D1. Pellini, W.S., "Guidelines for Fracture Mechanics Analysis of Pressure Tank Car Structural Integrity Factors," Report No. R-586, Association of American Railroads, June 1985.

D2. Pellini, W.S., "Introduction to AAR Guidelines for Fracture-Safe Design Involving Temperature-Transition Sensitive Structural Steels," Report No. R-383, Association of American Railroads, August 1979.

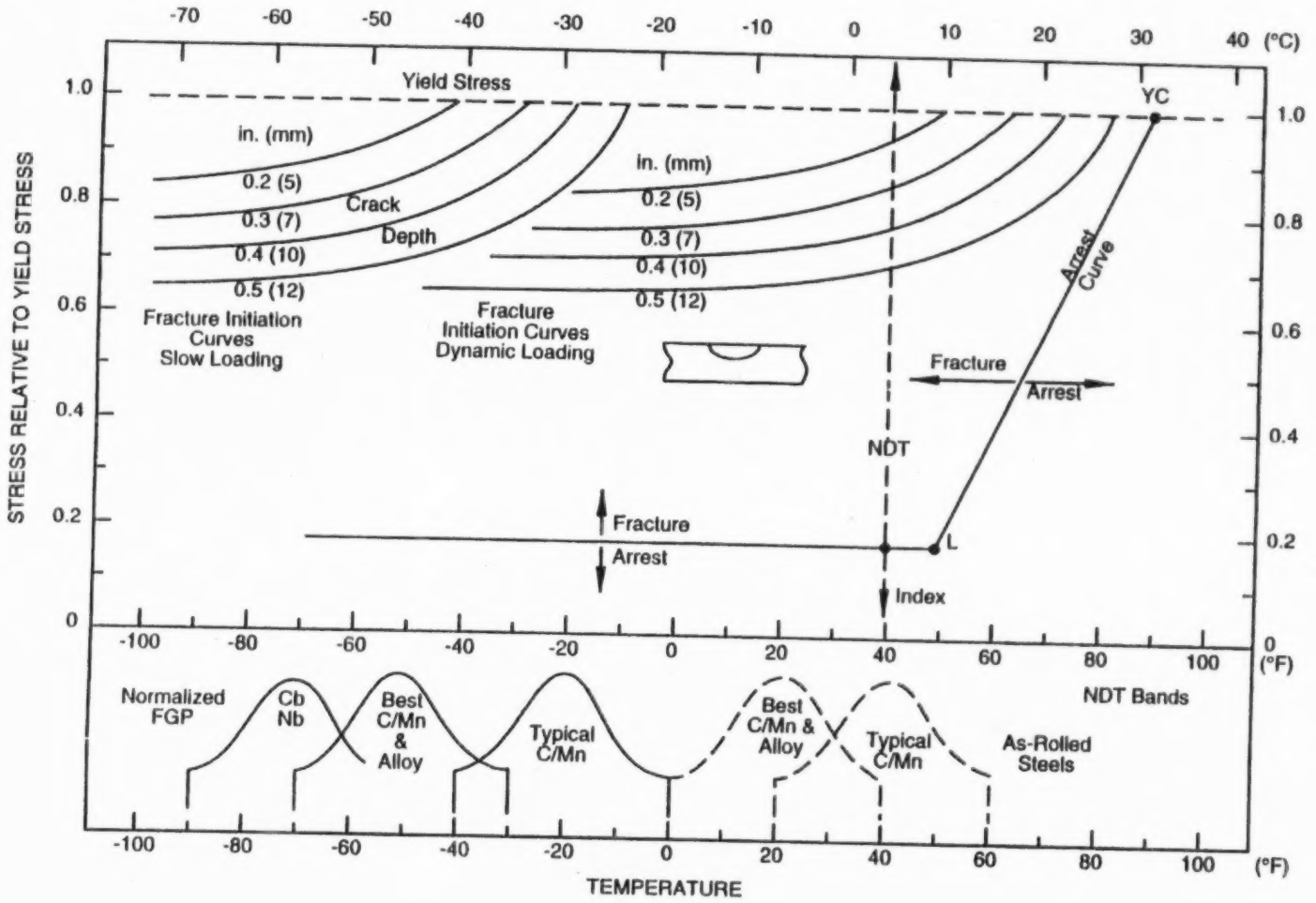


Figure D-1. Example of Fracture Analysis Graphs, Showing Comparisons of the Fracture Initiation Curves for Dynamic and Slow Loading Rates, and the Crack Arrest Envelope [D1]

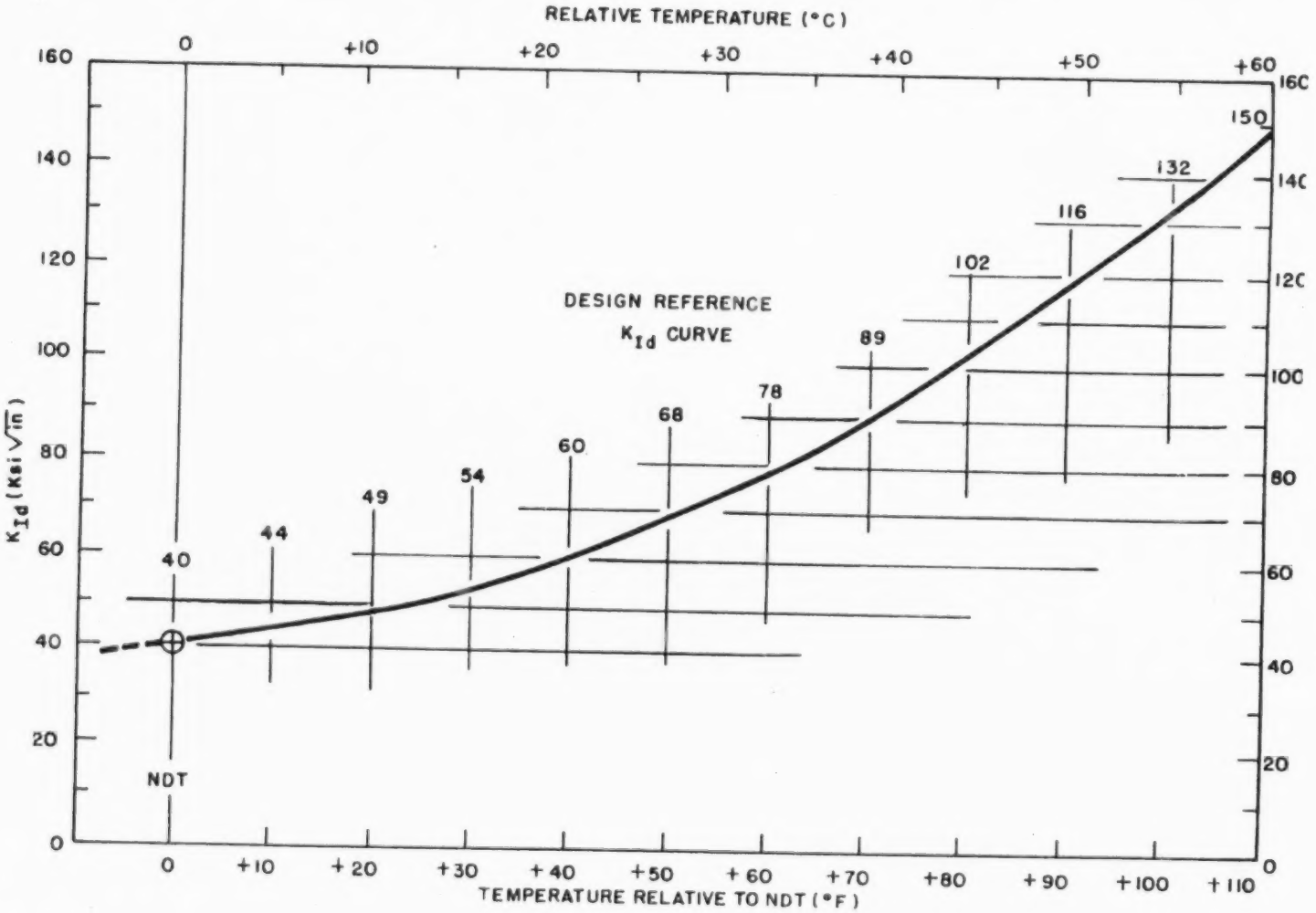


Figure D-2. AAR Design-Reference K_{Id} Curve [D2]